REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-03-

0108

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1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
14-02-2003	Final Technical Report	15 May 2000 -14 Febr. 2003

4. TITLE AND SUBTITLE
Investigation of the Quantum 1/f Effect and of Other Fluctuations in the Radiation-Hardening of Multiple-Satellite Systems

5a. CONTRACT NUMBER

5b. GRANT NUMBER
F49620-00-1-0306

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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8. PERFORMING ORGANIZATION REPORT NUMBERS-5-34218

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR
4015 Wilson Blvd.
Arlington, VA 22203-1954

20030508 086

NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED

13. SUPPLEMENTARY NOTES

14. ABSTRACT The author's quantum 1/f noise formulas were used for the first time here to calculate from first principles analytically, and to graph as a function of the absorbed dose, the radiation-induced 1/f noise increase in junction-type devices, such as junction-based photodetectors, BJTs, HBTs, mixers, etc. The same is done also for FET-type devices, such as FETs, or HFETs, yielding even a reduction of the equilibrium 1/f noise expected in high-mobility semiconductors for low radiation dose, and favoring them for radiation hardening. The same theory was adapted and used here for the first time to derive simple engineering formulas for the quantum 1/f effect in the radiation resistance of antennas from first principles. This allows for the optimization of the directivity of antenna arrays or of the response from multiple satellite systems in space. The same formulas were adapted and used here for the first time to derive analytical engineering formulas allowing for the quantum 1/f optimization of GaN/AlGaN HFETs, RTDs, biological and chemical resonant BAW and SAW quartz sensors, various silicon MEMS resonators, all types of spintronic devices, cavity resonators, nano-devices and bent ultra-thin semiconductor devices. This allows optimizing all these devices and systems for ultra-low 1/f noise and system phase noise, with staggering impact on major DOD instrumentation performance.

15. SUBJECT TERMS Quantum 1/f noise, 1/f Noise, Phase noise, Sensors, HFETs, RTDs, BJTs, MEMs resonators, BAW and SAW quartz resonators, Quartz microbalance, Radiation hardening, Nanotech Spintronics, Spin polarized transport, Oscillators, Resonators, Leeson formula, Satellites

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Dr. Gerald L. Witt
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
					703-696-8571

INVESTIGATION OF THE QUANTUM 1/F EFFECT AND OF OTHER FLUCTUATIONS IN THE RADIATION-HARDENING OF MULTIPLE-SATELLITE SYSTEMS

Grant No. F49620-00-1-0306

Final Technical Report Submitted to the Air Force Office of Scientific Research

by

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February 14, 2003

PERIOD COVERED: May 15, 2000 to February 14, 2003

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DURATION OF GRANT: 2.5 years

STARTING DATE: May 15, 2000

DISTRIBUTION STATEMENT A
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INVESTIGATION OF THE QUANTUM 1/F EFFECT AND OF OTHER FLUCTUATIONS IN THE RADIATION-HARDENING OF MULTIPLE-SATELLITE SYSTEMS

FINAL TECHNICAL REPORT SUBMITTED TO THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

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February 14, 2003

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INVESTIGATION OF THE QUANTUM 1/F EFFECT AND OF OTHER FLUCTUATIONS IN THE RADIATION-HARDENING OPTIMIZATION OF MULTIPLE-SATELLITE SYSTEMS

FINAL TECHNICAL REPORT SUBMITTED TO THE
US AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

A. STATUS OF EFFORT

We have performed an investigation of electronic 1/f noise at in the materials, devices and systems relevant to the US Air Force including the resulting phase noise, focusing on the effects of irradiation with γ-rays, neutrons, β and α particles. This also includes effects on arrays of satellites in space. The investigation used the author's quantum 1/f formulas. Our calculations indicate that low dose levels can under certain conditions lower the quantum 1/f noise of FET-type devices in which the mobility of the carriers is limited by electron-phonon scattering. Analytical expressions and graphical representation have been obtained. The latter show qualitatively the decreasing dependence of 1/f noise on the absorbed radiation dose. For junction devices, a linear increase of 1/f noise with the absorbed dose is obtained.

Phase noise is important for the Air Force. A 10 dB reduction in the noise floor will reduce the bit-error-rate by a factor of 10^{-6} in DSP systems that process real-time inputs in an aerospace battle environment. In a Doppler radar, from the R^{-4} law, a 24 dB reduction in the noise floor corresponds to a 4 fold increase in range R. Special emphasis was thus placed on quantum 1/f phase noise in RF and microwave devices, oscillators and systems in general. Leeson's formula was modified for this purpose radically by the inclusion of a new term proportional to the inverse fourth power of the loaded quality factor. This is essential for all high-stability systems. The present Technical Report discusses also the phase noise requirements for an array of satellites, and the physical basis of electronic noise control in radiation hardening. It is demonstrated that the quantum 1/f phase noise in the transmitters on individual satellites leads to an increased width of the coherent beam emitted by the array.

The new effect of quantum 1/f noise in the radiation resistance of antennas is introduced. This is important for low-power cosmic distance transmissions with highly directional, very well tuned antennas. It results in a 1/f spectral density of radiation resistance fluctuations inversely proportional to the quality factor of the antenna. The effect resonance frequency fluctuations in the antenna were found to be inversely proportional to the fifth power of the antenna quality factor. Solid state microwave generators of increased power can be obtained by using wide-bandgap materials, such as GaN. We have obtained from first principles an analytical formula for quantum 1/f noise in GaN/AlGaN HFETs that agrees with the experimental data, and allows optimization of the device and system. It yields a strong 1/f noise increase with gate voltage.

1/f noise in resonant tunneling diodes (RDTs), biological-chemical sensors, spintronics and bent ultra-thin semiconductor samples or integrated circuits was also described for the first time with exact engineering formulas, allowing for their optimization. For RTDs, the 1/f noise is found to be proportional to the squared voltage V_v for which the valley in the graph of the current occurs. It has a spectrum of 10^{-7} for fractional current fluctuations at V_v=0.4V. The sensors are optimized by making them either very small compared with the coherence length of phonons in the quartz, or very large. Bending also increases noise in ICs based on junction devices and may decrease the noise in certain conditions for ICs based on FETs and HFETs.

B. ACCOMPLISHMENTS/NEW FINDINGS

B1. Permanent Conventional Quantum 1/f Noise Reduction in Semiconductor Samples and FET/HFET-Type Devices Through Irradiation

Introduction. This 1/f noise reduction is limited to very small samples, for which the conventional quantum effect is not masked by the coherent quantum 1/f noise; see [1]-[72] for both, including theory and experiment. It will be particularly noticeable in good samples and FET/HFET devices, that had a relatively high mobility, limited by lattice scattering, and become more defect-scattering-limited after the irradiation. The effect is observed only in stable samples or devices, i.e., at sufficient time after the irradiation. To verify the effect, the 1/f noise is measured at low temperature before irradiation. The sample is brought to room temperature, is irradiated, and kept at room temperature for a week. It is then returned to the same low temperature, and measured under the same conditions as before, to determine the 1/f noise in stable condition after the irradiation. The renewed cooling is necessary, because normally, even after a week the irradiated samples/devices are not stable enough to avoid the superposition of a dominant $1/f^2$ component caused by linear drift.

Derivation. In general, Matthiessen's rule allows us to write for the resulting carrier mobility μ

$$1/\mu=\Sigma_i(1/\mu_i), \tag{1.1}$$

where μ_i is the mobility that would be observed if only scattering process "i" would act. The quantum fluctuations

$$\delta\mu/\mu^2=\Sigma_i(\delta\mu_i /\mu_i^2), \tag{1.2}$$

are multiplied by μ, squared, averaged (quantum expectation value) and referred to the unit frequency interval to obtain the spectral density of fractional fluctuations

$$S_{\delta\mu/\mu}(f) = \Sigma_i(\mu/\mu_i)^2 S_{\delta\mu i/\mu i}(f). \tag{1.3}$$

This is based on the statistical independence of fluctuations in the cross section or rate of the scattering process i from all others. All $S_{\delta\mu i/\mu i}$ decrease ~1/N, with N the total number of carriers.

In particular, let n_o be the total concentration of all types of impurity and defect scattering centers, and n' the additional concentration of defect scattering centers introduced by the irradiation. Then Eq. (1.1) yields

$$1/\mu_o = 1/\mu_{od} + 1/\mu_l \tag{1.4}$$

for the initial mobility, and

$$1/\mu = 1/\mu_d + 1/\mu_l = (1+r)/\mu_{od} + 1/\mu_l, \tag{1.5}$$

where $r=n'/n_{od}$ is the ratio between the additional defect concentration n' created by the irradiation and the pre-existing defect concentration n_{od}. We have assumed that if lattice scattering would be absent, the mobility μ_d expected after the irradiation would be reduced by a factor 1+r when compared with its initial value μ_{od}, present before irradiation. This is to be expected, since the frequency of scattering is proportional to n' and therefore with the absorbed dose of radiation J in Sv (sieverts)

$$n'=\kappa J; \qquad \kappa=\rho\sigma_d/E(\sigma_{tot}-\sigma_s), \tag{1.6}$$

where κ is a coefficient defined for the given semiconductor material of density ρ as the product of the atomic cross section for defect creation σ_d in bn (barns) with ρ in Kg/m^3, divided by the energy of the particles in joules and by the total atomic effective absorption cross section $\sigma_{tot}-\sigma_s$. Here σ_s is the scattering cross section, while σ_{tot} is the total attenuation cross section, both in bn. Note that 1Sv is 100 rad, and 1 rad =100 erg/g. n' is obtained in m^{-3}. Note that σ_d is dependent on the temperature of the lattice through a Debye-Waller factor for the part involving displacement of lattice points with creation of interstitials. For neutrons, σ_d includes the nuclear capture cross section, etc.

Initially, for the noise measurement before irradiation, we can thus write

$$S_{\delta\mu/\mu}(f) = (\mu_o/\mu_{od})^2 S_d + (\mu_o/\mu_l)^2 S_l = (1-\mu_o/\mu_l)^2 S_d + (\mu_o/\mu_l)^2 S_l \tag{1.7}$$

where $S_d = S_{\delta\mu d/\mu d}(f)$ and $S_l = S_{\delta\mu l/\mu l}(f)$ are the quantum 1/f spectral densities of fractional mobility fluctuations calculated for the elementary act of defect scattering of a current carrier, and for the elementary act of lattice scattering, respectively. On the other hand, after the irradiation, at the same temperature, in stable (in fact, metastable) conditions, we obtain

$$S'_{\delta\mu/\mu}(f) = (1+r)^2(\mu/\mu_{od})^2 S_d + (\mu/\mu_l)^2 S_l = (1-\mu/\mu_l)^2 S_d + (\mu/\mu_l)^2 S_l. \tag{1.8}$$

Neglect now that both S_d and S_l decrease like 1/N. From Eqs. (1.7) and (1.8) we derive the ratio

$$\boxed{R = S'/S = [(\mu_l-\mu)^2 S_d + \mu^2 S_l]/[(\mu_l-\mu_o)^2 S_d + \mu_o^2 S_l]} \tag{1.9}$$

between the 1/f noise power after and before irradiation. Since $\mu<\mu_o$ and $S_d<<S_l$, this ratio is less tan unity. Neglecting S_d, (because conventional quantum 1/f effect is proportional to the square of the scattering angle, and defect scattering is mainly small angle scattering) we obtain

$$\boxed{R\approx\mu^2/\mu_o^2;} \qquad R\approx 1/[1+r(1+\mu_o/\mu_l)]^2; \qquad R\approx 1/[1+(\kappa J/n_o)(1-\mu_o/\mu_l)]^2 = 1/(1+AJ)^2, \tag{1.10}$$

where $A=(\kappa/n_o)(1-\mu_o/\mu_l)$ is a constant (see Fig. 1). **Rms Q1/f noise is thus reduced like μ..** On the other hand, if defect scattering was negligible before irradiation, $n_{od}=0$ and $\mu_o=\mu_l$. This yields

$$R=\mu^2/\mu_o^2 + (1-\mu/\mu_o)^2(S_d/S_l). \tag{1.11}$$

This prediction of the quantum 1/f theory is remarkable, because it is counterintuitive. It is usually masked in the short run by the transient effects discussed in Sec. B3 below, and by relaxation of the defect concentration towards the equilibrium concentration. This relaxation contributes a large temporary $1/f^2$ noise spectral component, as does any linear drift present

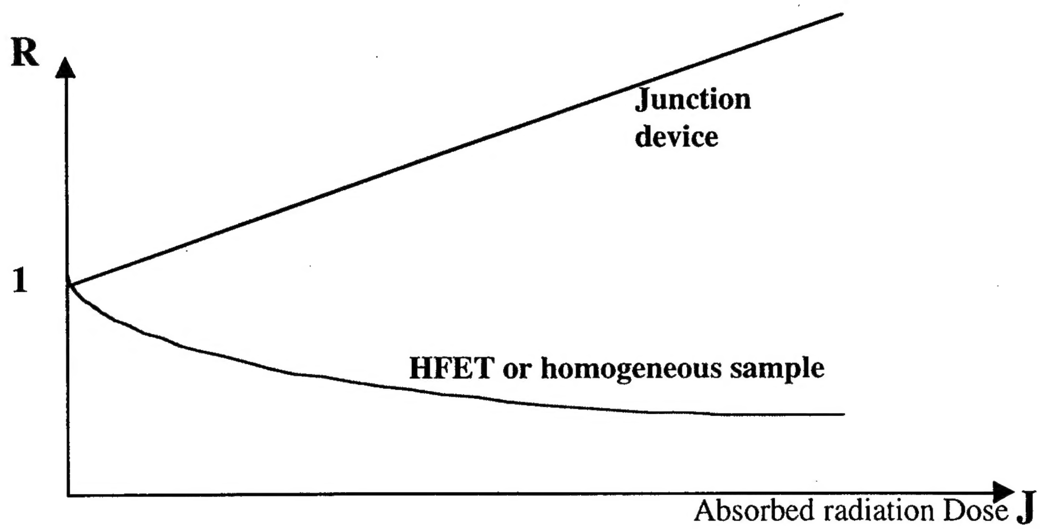

Fig. 1. Dependence of the Noise Modification Ratio R on the absorbed radiation dose J

during the noise measurement. Note that the decrease can be stronger, since N is likely to go up.

B2. Permanent Quantum 1/f Noise Increase in Junction-Type Devices

Introduction. Junction-type devices contain pn junctions perpendicular to the current density vector. In this case, the current is determined either by diffusion, or, particularly at lower temperatures, by recombination in the space charge region of the junction (or by both, in the transition interval of temperatures). Quantum 1/f fluctuations in the diffusion constant (related to mobility fluctuations through the Einstein relation) and in the recombination rates, both at the surface and in the bulk, are causing the 1/f noise in this case. Not all carriers are involved, but only those emerging from the scattering or recombination process mentioned. Their number is $N=I/e\tau$, where τ is the lifetime of the carriers, I the current through the junction, and e the elementary charge. Since the number of carriers enters in the denominator, the noise power is proportional to the first power of the current I for forward bias larger than kT/e, whereas it goes like I^2 in samples and FET/HFET devices. The main radiation effect comes now from the drastic reduction of the lifetime τ in the denominator, causing an increase of 1/f noise with irradiation in junction devices. There is also a small shift in the current limiting mechanism (mainly in the transition region) and a change in the quantum 1/f coefficient for diffusion/mobility fluctuations as mentioned in the previous Sec. B1, but that is usually a much smaller effect here. On top of everything are, of course, the large transient radiation effects to be discussed in Sec. B3.

Derivation. The lifetime of the carriers decreases with the radiation dose J

$$1/\tau = 1/\tau_o + \sigma v n' = 1/\tau_o + \sigma v \kappa J, \qquad (2.1)$$

where κ is the factor of proportionality introduced in Eq. (1.6) above, v is the rms speed of the electrons in the semiconductor, and σ is the well-known Conwell-Weisskopf cross section if the

defects are ionized. The 1/f noise is calculated below first for a pn junction.

For a diffusion limited n^+-p junction the current is controlled by diffusion of electrons into the p - region over a distance of the order of the diffusion length $L = (D_n\tau_n)^{1/2}$ which is shorter than the length w_p of the p - region in the case of a long diode. If N(x) is the number of electrons per unit length and D_n their diffusion constant, the electron current at x is

$$I_{nd} = - eD_n dN/dx, \tag{2.2}$$

where we have assumed a planar junction and taken the origin x = 0 in the junction plane. Diffusion constant fluctuations, given by kT/e times the mobility fluctuations, will lead to local current fluctuations in the interval Δx

$$\delta\Delta I_{nd}(x,t) = I_{nd}\Delta x\delta D_n(x,t)/D_n. \tag{2.3}$$

The normalized weight with which these local fluctuations representative of the interval Δx contribute to the total current Id through the diode at x = 0 is determined by the appropriate Green function and can be shown to be (1/L)exp(-x/L) for $w_p/L >> 1$. Therefore the contribution of the section Δx is

$$\delta\Delta I_d(x,t) =(\Delta x/L)\exp(-x/L)I_{nd}\delta D_n(x,t)/D_n, \tag{2.4}$$

with the spectral density

$$S_{\Delta Id}(x,f) = (\Delta x/L)^2 \exp(-2x/L)\, I_{nd}^2\, S_{Dn}(x,f)/D_n^2. \tag{2.5}$$

For mobility and diffusion fluctuations the fractional spectral density is given by $\alpha_{Hnd}/fN\Delta x$, where α_{Hnd} is determined from quantum 1/f theory. With Eq. (8.1) below we obtain then [20]

$$S_{\Delta Id}(x,f) = (\Delta x/L^2)\exp(-2x/L)(eD_n dN/dx)^2\alpha_{Hnd}/fN. \tag{2.6}$$

The electrons are distributed according to the solution of the diffusion equation, i.e.

$$N(x) = [N(0) - N_p] \exp(-x/L); \qquad dN/dx = -\{[N(0) - N_p]/L\} \exp(-x/L). \tag{2.7}$$

Substituting into Eq. (2.6) and simply summing over the uncorrelated contributions of all intervals Δx, we obtain

$$S_{Id}(f) = \alpha_{Hnd}(eD_n/L^2)^2 \int[N_o-N_p]^2 e^{-4x/L}dx/\{[N(0) -N_p]\, e^{-x/L} + N_p\}. \tag{2.8}$$

We note that $eD_n/L^2 = e/\tau_n$. With the expression of the saturation current $I_o = e(D_n/\tau_n)^{1/2}N_p$ and of the current $I = I_o[\exp(eV/kT) - 1]$, we can carry out the integration

$$S_{Id}(f) = \alpha_{Hnd}(eI/f\tau_n) \int du/(au + 1) = \alpha_{Hnd}(eI/f\tau_n)\, F(a). \tag{2.9}$$

Here we have introduced the notations

$$u = \exp(-x/L), \quad a = \exp(eV/kT) - 1,$$

$$F(a) = 1/3 - 1/2a + 1/a^2 - (1/a^3)\ln(1+a). \tag{2.10}$$

Eq. (2.9) gives the diffusion noise as a function of the quantum 1/f noise parameter α_{Hnd}. A similar result can be derived for the quantum 1/f fluctuations of the recombination rate r in the bulk of the p - region, the only difference being the presence of α_{Hnr} instead of αH_{nd} in Eq. (2.9). The total noise is the given by Eq. (2.9) with α_{Hnd} replaced by the sum $\alpha_{Hnd} + \alpha_{Hnr}$

$$\boxed{S_{Id}(f) = (\alpha_{Hnd} + \alpha_{Hnr})(eI/f\tau_n)F(a).} \qquad (2.11)$$

From Eq. (2.1) we obtain for n'

$$\boxed{S_{Id}(f) = (\alpha_{Hnd} + \alpha_{Hnr})(eI/f)F(a)(1/\tau_o + \sigma v \kappa J),} \quad \boxed{R \approx (1/\tau_o + \sigma v \kappa J),} \qquad (2.12)$$

which clearly displays a linear increase of 1/f noise with the applied dose (Fig. 1).

The radiation-induced increase in the 1/f noise power of the emitter junction is the most important, because it appears increased by the square of the amplification factor β in the collector circuit. However, the noise increase in the collector junction yields also a considerable contribution. The overall increase will be given by a linear equation similar to what we have in Eq. (22) for a single junction. We conclude that according to the Q1/f theory, the junction devices will show a much larger noise increase. In the long run, as we noticed above, even a decrease of 1/f noise is likely in good FET/HFET devices.

B3. Transient Radiation Effects in Semiconductor Devices

These effects are mainly caused by a large flood of current carriers produced by γ-rays by internal photoelectric effect (e.g., excitation of electrons from the conduction band and from localized energy levels), by Compton effect and, if they have more than 1 MeV, also by pair formation. Just as we saw above for noise, this affects junction devices again more than FET/HFET devices.

Measures suggested here by us to prevent large damaging transients from BJTs and HBTs, would consist of inclusion of a sufficiently large, normally reverse-biased, pn junctions *both* before the emitter connection, *and* after the collector connection of a bipolar transistor. Both diodes are made particularly radiation sensitive, and have the other end grounded. The same effect mentioned above will occur then also in the diodes, and will provide a temporary shunt, thereby exactly compensating the extra currents to be expected from the transistor

B4. Noise and Quantum 1/f Effect as Indicators of Radiation Damage; The Principle of Auto-Repair

Radiation damage in electronic devices and integrated circuits was studied by many authors, in particular during the last 2 decades. Among the main specialists we mention R.D. Schrimpf for silicon devices and R. Zuleeg who pioneered the work on GaAs particularly important for VHSIC applications. An excess of As turned out to be useful for the automatic defect repair, or healing, mechanism. Electronic noise and the quantum 1/f effect can be used to indicate the presence of radiation damage and to trigger automatic repair actions through annealing, self-testing and self-reconfiguration. Furthermore they can be used to study the mechanism of cumulative radiation-induced damage for various types of particulate and electromagnetic radiation including γ rays, and for studying the time-dependent effects of large dose-rates.

A review of the literature shows an enormous amount of activity in the field of radiation

hardening during the last few decades, most of it published in the IEEE Transactions on Nuclear Science. A detailed study of the more recent contributions [71]-[113], performed by the author, indicates that the present situation is dominated by empirism and by studies performed on a particular type of device, for a particular application or class of radiation exposure situations. Many results are reflecting the presence of $1/f^2$ components arising from the linear drift caused by the return of the system to a state closer to the true equilibrium state. Indeed, the power spectrum of a linear drift is known to be proportional to 1/f, and very large at low frequency, causing the total power spectral density to be steeper.

What seems to be missing is a fundamental, all-encompassing theory which can be easily applied to all situations. However, such a general theory is extremely difficult to create and may not be possible without empirical elements, and does not represent a reasonable alternative to using the experience of specialists who have worked in this field for a long time and have accumulated a tremendous experience. *Nevertheless, for a more restricted domain of low-dose and low dose-rate radiation damage, such as caused by the unshielded cosmic and solar radiation background, the task is feasible, because we know the formulas describing shot, GR, thermal, non-fundamental 1/f, and quantum 1/f noise.*

For instance, the occurrence of a lorentzian component (bump) in the noise spectrum, of the form

$$S(f) = 4\tau/(1 + 4\pi^2 f^2) \qquad (4.1)$$

indicates the presence of carriers with the lifetime τ.

In the absence of pn junctions, the quantum 1/f noise does not change monotonously as a function of radiation dose at low radiation dose values. It first decreases and then increases when more radiation is absorbed. Indeed, in small monocrystalline probes and devices, with large mobility limited by lattice scattering, the presence of a small radiation dose causes defects which lower the conventional quantum 1/f noise because they introduce a larger fraction of low-angle scattering into a system dominated by large angle lattice scattering, including umklapp and intervalley scattering. This is noticed when we apply the formula

$$S_{\delta\mu/\mu}(f) = \sum_i (\mu/\mu_i)^2 S_{\delta\mu_i/\mu_i}(f) \qquad (4.2)$$

which shows how the quantum 1/f effect in different scattering mechanisms determines the total quantum 1/f mobility noise spectrum. Indeed, the $S_{\delta\mu_i/\mu_i}(f)$ factors are *proportional to the squared momentum change of the scattered carriers. Since the momentum changes are smaller in defect scattering, we expect an initial decrease of 1/f noise when small radiation doses are applied, provided the defects have become stable in time.*

At larger radiation doses the current paths change, leading to increased quantum 1/f noise and increased accidental (non-fundamental) 1/f noise.

Micro-processors, comparing the actual noise spectrum with pre-calculated spectra stored in the memory, can therefore determine the presence and type of radiation damage. They can then trigger the optimal annealing process corresponding to the type of radiation damage at hand.

B5. Phase-Coherence and Low Phase Noise in Multiple Satellites

An array of satellites (Fig. 2), orbiting the earth with parallel antennas, can be used to selectively receive and/or emit electromagnetic waves from/into a very well defined direction whose angular width is given by the diffraction limit

$$\delta_o\theta = \lambda/2Na\cos\theta \tag{5.1}$$

in the absence of phase noise. This is caused by the uncertainty principle. Here a is the distance between the N satellites forming the array and θ is the angle between the direction of the beam and the normal to the linear array of N satellites. The length of the array is then $L=Na$ and the mean phase difference between neighboring satellites is

$$\phi = 2\pi a\sin\theta/\lambda. \tag{5.2}$$

In the presence of phase noise of variance $<(\delta\phi)^2>$, the beam direction error $\delta\theta$ will be the sum of both errors: $\delta\theta = \delta_\phi\theta + \delta_o\theta$. The variance is therefore approximated by

$$<(\delta\theta)^2> = <(\delta_\phi\theta)^2> + <(\delta_o\theta)^2> = <(\delta_\phi\theta)^2> + (\lambda/2Na\cos\theta)^2. \tag{5.3}$$

From Eq.(5.2) we obtain

$$\delta_\phi\theta = (\lambda/2\pi a\cos\theta)\delta\phi. \tag{5.4}$$

Therefore, Eq. (5.3) becomes

$$<(\delta\theta)^2> = <(\delta_\phi\theta)^2> + <(\delta_o\theta)^2> = (\lambda/2\pi a\cos\theta)^2<(\delta\phi)^2> + (\lambda/2Na\cos\theta)^2$$

$$= (\lambda/2\pi a\cos\theta)^2[<(\delta\phi)^2> + (\pi/N)^2]. \tag{5.5}$$

It is thus desirable to reduce the phase noise variance to a value below the threshold $(\pi/N)^2$.

According to the quantum 1/f theory [1]-[72] and also for most non-fundamental forms of electronic noise present in oscillating systems and resonators included in the multiple satellites system, the frequency fluctuations are caused by fluctuations in the dissipation. Therefore, as first found by the author [14] in 1978, the spectral density of fractional fluctuations $\delta\omega$ in the frequency ω is

$$S_{\delta\omega/\omega}(f) = (1/4Q^4)S_{\delta\gamma/\gamma}(f). \tag{5.6}$$

Here $S_{\delta\gamma/\gamma}(f)$ is the spectral density of fractional fluctuations $\delta\gamma/\gamma$ in the dissipation rate γ, and Q is the quality factor of the resonant system, including resonator and oscillator. This resulting Q is close to the Q of the resonator, if a good resonator is used. The spectral density of fractional frequency fluctuations $S_{\delta\omega/\omega}(f)$ is connected to the spectral density $S_{\delta\phi}(f)$ of phase fluctuations by

$$S_{\delta\omega/\omega}(f) = (2\pi f/\omega)^2S_{\delta\phi}(f) \tag{5.7}$$

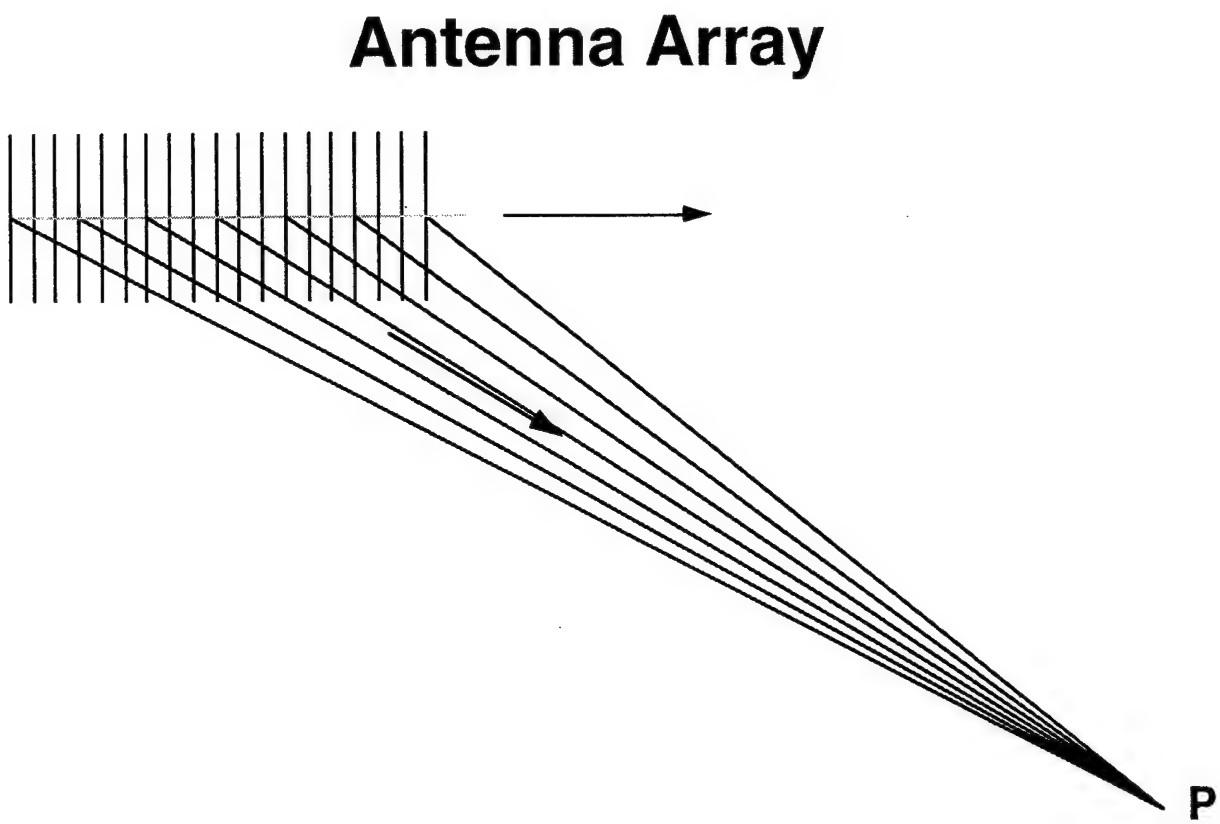

Fig. 2: An antenna array generates a coherent superposition of beams from each antenna in the array, with a resulting angular width given by the diffraction limit $\delta_o\theta = \lambda/2Na\cos\theta$ in the absence of phase noise.

Consequently, from Eqs. (5.5), (5.6) and (5.7) we obtain

$$\int(\omega/2\pi f)^2(1/4Q^4)S_{\delta\gamma/\gamma}(f)df < (\pi/N)^2 \tag{5.8}$$

as the required condition to be satisfied by the maximal allowed noise spectral density of the electronic systems used. Here the integral is extended over the frequency interval defined by $f_o=1/T$ as the lowest frequency and $f=1/t$ as the highest frequency. T is the reciprocal time of a given transmission into a well-defined direction. On the other hand, the upper limit can be extended to infinity, due to the factor f^2 in the denominator of Eq. (5.8), which insures rapid convergence.

The author has generalized Eq. (5.8) also to the case of a 2-dimensional array of satellites. For a three dimensional array, only certain emission directions are possible at any given frequency, so this case was not considered, because it does not allow a beam sweep at constant frequency.

In the presence of the cosmic and solar radiation, and of radiation caused by hostile actions, the satellites need an automatic radiation damage removal system operative at the level

of individual devices, integrated circuits and macroscopic electro-physical as well as electro-optical components. This system can be based on several parameters, and can be optimized for the given performance criteria, including device level and system level stochastic noise and quantum 1/f noise.The latter is described for the first time as a result of this project, from first principles, in the next Section B6, below.

In addition, the satellites need to incorporate adaptive stealthing capabilities over several optical, microwave and radar frequency domains. This can be achieved on the basis of the method developed by the author in US Patent #185979: "Absorptive Coating for the Reduction of the Reflective Cross Section of Metallic Surfaces and Control Capabilities Therefor".

B6. Quantum 1/f Effect in the Radiation Resistance of Antennas

1. Introduction. It is well known that kinetic coefficients such as the electrical resistance of conductors and semiconductors exhibit quantum 1/f fluctuations caused by the quantum 1/f effect in the scattering cross sections of the current carriers. Is the radiation resistance of antennas an exception? The present Section tries to answer this question, and to suggest ways in which the quantum 1/f noise in the radiation resistance can be experimentally verified.

According to the general quantum 1/f formula [1]-[13] the spectral density of fractional fluctuations in any physical cross section or process rate Γ is

$$\Gamma^{-2}S_\Gamma(f)=2\alpha A/f \tag{6.1}$$

with $\alpha=e^2/\hbar c=1/137$ and $A=2(\Delta J/ec)^2/3\pi$. This is the quantum 1/f effect in any physical scattering rate Γ, and $\mathbf{J}=e\mathbf{v}$ is the current of the scattered particles of charge e and velocity $\mathbf{v}$. The "physical cross sections" and "process rates" are defined by us to contain the quantum 1/f fluctuations, in addition to the quantum mechanical expectation value. Here $\Delta\mathbf{J}$ denotes the current change caused by the scattering process.

2. Quantum 1/f antenna loss rate fluctuations. In the case of an antenna, the collective "scattering" process affected by quantum 1/f fluctuations is the process of radiation of one quantum of the antenna's oscillation energy quanta $\varepsilon=\hbar\omega$. Setting

$$a\mathbf{J} = d\mathbf{P}/dt = \dot{\mathbf{P}}, \tag{6.2}$$

where $\mathbf{P}$ is the vector of the dipole moment of the antenna of length a, we obtain for the fluctuations in the rate Γ of removal of oscillation energy quanta $\varepsilon=\omega\hbar$ from the main antenna oscillation mode, the spectral density

$$S_\Gamma(f) = \Gamma^2 4\alpha(\Delta\dot{\mathbf{P}})^2/3f\pi e^2c^2, \tag{6.3}$$

where $(\Delta\dot{\mathbf{P}})^2$ is the square of the dipole moment rate change associated with the process causing the radiative removal of a quantum $\varepsilon=\omega\hbar$ from the main oscillation mode. To calculate it, with $\mathbf{J}a = dP/dt$, we write the energy W of the antenna mode in the form

$$W \equiv n\omega\hbar = (1/2a^2)L_{eff}(dP/dt)^2 = (1/2a^2)L_{eff}(\dot{\mathbf{P}})^2; \tag{6.4}$$

The factor two including the potential (capacitive) energy contribution is automatically included because we define $\dot{\mathbf{P}}$ here to represent precisely the amplitude of the antenna dipole moment rate of change, rather than the oscillating instantaneous value. Here L_{eff} is the effective inductance of the antenna dipole. Applying a variation $\Delta n=1$ which corresponds to the spontaneous emission of one quantum, we get

$$\Delta n/n = 2|\Delta\dot{\mathbf{P}}|/|\dot{\mathbf{P}}|, \text{ or } \Delta\dot{\mathbf{P}} = \dot{\mathbf{P}}/2n. \tag{6.5}$$

Solving Eq. (6.4) for $\dot{\mathbf{P}}$ and substituting, we obtain

$$|\Delta\dot{\mathbf{P}}| = (\omega\hbar\, a^2/2nL_{eff})^{1/2} \tag{6.6}$$

Substituting $\Delta\dot{\mathbf{P}}$ into Eq. (6.3), we get $4\alpha(\omega\hbar/2nL_{eff})/3\pi e^2c^2$

$$\Gamma^{-2}S_\Gamma(f) = 2\alpha\hbar\,\omega a^2/3n\pi c^2 fL_{eff}e^2 \equiv \Lambda/f. \tag{6.7}$$

This result is applicable to the fluctuations in the radiative loss rate Γ of the antenna.

3. 1/f Fluctuations of the antenna resonance frequency and radiation resistance. The corresponding fluctuations in the resonance frequency of the antenna are given by [14]

$$\omega^{-2}S_\omega(f) = (1/4Q^4)(\Lambda/f) = \alpha\hbar\,\omega a^2/6n\pi c^2 fL_{eff}e^2Q^4, \tag{6.8}$$

where Q is the quality factor of the single-mode antenna considered.

Eq. (6.7) implies fluctuations of the radiation resistance of the antenna, defined by

$$R_r = \hbar\,\omega\Gamma/I^2. \tag{6.9}$$

The corresponding spectral density of fractional fluctuations of the radiation resistance R_r is thus the same

$$R_r^{-2}S_{Rr}(f) = 2\alpha\hbar\,\omega a^2/3n\pi c^2 fL_{eff}e^2 \equiv \Lambda/f. \tag{6.10}$$

This can be further simplified. Indeed, if the antenna is left to ring out without excitation, the part of the energy decay rate caused by the radiation is given by

$$-dW/dt \equiv P_r = W/\tau. \tag{6.11}$$

Equating the last 2 terms, one obtains

$$2(d^2P/dt^2)/3c^3 = L_{eff}J^2/2\tau. \tag{6.12}$$

With

$$Ja = dP/dt \tag{6.13}$$

this equation becomes

$$L_{eff} = 4\omega^2 a^2 \tau / 3c^3. \quad (6.14)$$

Substitution into Eq. (6.10) yields then

$$S_{\delta R/R} = [2n\pi f\tau\omega]^{-1} = [2n\pi f\omega/2\gamma]^{-1} = [2n\pi fQ]^{-1}. \quad (6.15)$$

Here we used the amplitude attenuation coefficient $\gamma=1/2\tau$ and the antenna quality factor Q = w/2g = wt. Eq. (6.15) has all the earmarks of a basic quantum 1/f formula applicable with no change in all systems of units, with considerable generality. It should be verified experimentally. All other equations are easily translated from the Gaussian to the International System.

B7. Theory of Quantum 1/f Noise in GaN/Al0.15Ga0.85N HFETs

The present Section applies the quantum theory of 1/f noise to predict the 1/f fluctuations measured on GaN doped channel HFETs and to compare the experimentally measured values of the effective Hooge parameter with the theoretical value. This theory has been successfully used and verified by van der Ziel, used and developed by C.M. Van Vliet, M. Tacano, G. Bosman, K. Gopala, A. Widom, Y. Srivastava, S. Bandyopadhyay, A. Balandin, K. Wang, by us, and by many other authors.

7.1. Uniform channel approximation

To apply the theory, the HFET channel is first considered here to be similar to a parallelipipedic sample of dimensions 50mm gate width, 500Å channel depth and 1 mm gate length. In second approximation, the reduction in channel conductivity from source to drain is also taken into account, in order to find the effective quantum 1/f parameter that is to be compared with the measured Hooge parameter. In the uniform channel approximation we expect from the 2 1017 cm-3 doping level a number of electrons per unit channel length of

N'=50mm ¥ 0.05mm ¥ 2 1017cm-3 = 5 109cm-1 (7.1)

at flatband. This allows us to find the "s"-parameter present in of the general quantum 1/f formula. This "coherence parameter" is the number of charge carriers in a thin salami-slice-like section of the sample. "Thin" means twice the classical radius ro=e2/mc2 = 2.84 10-13 cm of the electron. In our case, the parameter is

s = 2 ¥ 5 109 cm-1 ¥ 2.84 10-13 cm = 2.84 10-3. (7.2)

Knowledge of the coherence parameter s allows the calculation of the quantum 1/f noise parameter

ao =[2a/p(1+s)]{s + (2/3)(Dv/c)2}. (7.3)

Here $\alpha=e^2/\hbar c=1/137$. The terms in curly brackets correspond to the coherent and conventional quantum 1/f effect contributions respectively. The effective velocity change Δv of the current

carriers is present in the conventional term. It is determined by including the average quadratic momentum changes experienced by the current carriers in all scattering processes that limit the mobility of the carriers: impurity scattering, acoustical and optical phonon scattering, inter-valley scattering and umklapp-scattering. They are included with weights of $(\mu/\mu_I)^2$, where μ is the resulting mobility of the carriers and μ_I is the (larger) mobility that would be obtained if only the scattering process labeled with the subscript I would be active. The applicable formula is

$$(\Delta v/c)^2 = \Sigma_I(\mu/\mu_I)^2(\Delta v/c)_I^2. \tag{7.4}$$

The velocity change $(\Delta v/c)_I^2$ is the appropriate average over the occupied energy levels in the band in which the carriers are located energetically. In our case it is the conduction band for electrons in the channel of the HFET. This complicates a more exact calculation of the conventional 1/f term somewhat, unless it is a semiconductor material for which such calculations have been performed already. Usually it is sufficient to estimate the conventional quantum 1/f noise by including the largest contribution, which is from umklapp or inter-valley scattering. In our case this yields for the GaN channel the second term in curly brackets in the form

$$(2/3)(\hbar G/cm_{eff})^2 = (2/3)(\hbar 2\pi/acm_{eff})^2 = (2/3)[h/c3.2\ 10^{-8}cm\times 0.2m_e]^2 = 4.5\ 10^{-4}. \tag{7.5}$$

However, according to Eq. (7.2), the coherent quantum 1/f vestige given by the first term s in curly brackets is more than six times larger. This places us in the difficult transition region between coherent and conventional quantum 1/f effect. In that situation, due to the proportionality of s with the number of carriers N' per unit length, due to s<<1 being negligible in the denominator, and due to the preponderance of the coherent quantum 1/f term, the measured 1/f noise (Hooge) parameter will be proportional to N', as indicated by Eq. (7.3). *This accounts for the increase of the experimentally determined α_H with V_G^* that is evident in Table 1 of the previous paper, as we shall see in detail below.* Indeed, V_G^* is the amount by which the gate voltage V_G exceeds its threshold value V_T. The number of carriers N' per unit of channel length is known to increase with V_G^*. The factor in rectangular brackets in Eq. (7.3) is

$$2\alpha/\pi(1+s) = 2/137\pi(1+s) = 4.65\ 10^{-3}. \tag{7.6}$$

The two terms, coherent and conventional, in Eq. (7.3) yield

$$\alpha_0 = [2\alpha/\pi(1+s)]\{s + (2/3)(\Delta v/c)^2\} = 1.32\ 10^{-5} + 4.55\ 10^{-6} = 1.78\ 10^{-5} \tag{7.7}$$

for the resulting quantum 1/f parameter at flatband.

In the previous experiments [121] the applied drain voltage used to measure the Hooge parameter was V_{DS}=5V. This caused the channel cross section and the number of carriers per length unit to decrease dramatically from source to drain. Nevertheless, the effective Hooge constant was defined in terms of a constant channel cross section and carrier concentration. Therefore, either the measured Hooge constant needs to be corrected for channel non-uniformity, or the calculated quantum 1/f parameter must be adjusted for channel non-uniformity. Both

ways allow for a meaningful comparison of the Hooge parameter with the resulting quantum 1/f parameter. We choose the first path because it yields Hooge parameters which can be better compared with those found in other devices with different geometry. In general, we choose to compensate for geometrical effects and to obtain geometry-independent results with universal applicability.

7.2. Below saturation: effect of channel non-uniformity

Using notations similar to those chosen in Warner and Grung, Eq. 5-9 in [122], we will describe the effect of a small channel non-uniformity on the observed 1/f noise. We choose the y-axis along the electronic drift. The latter occurs over a distance Y slightly longer than the 50 μm gate length, from source to drain. The x-axis is oriented vertically down from the gate along the channel thickness X, and the z-axis is also across the current, along the (usually larger) gate width Z.

a. Approximation neglecting the statistical distribution of the carriers

In this approach, the number of charge carriers is simply approximated by the net induced charge, divided by the charge of the electron. This approximation is limited to above-threshold conditions below saturation, neglects the conductance from carriers of both signs that compensate their charges, and neglects the Fermi statistical distribution of carriers. It is certainly not applicable when the number of carriers, or the conductance predicted, approach, or actually become, negative or zero. With these limitations, the element of resistance dR along the current can be written, [122], [123]

$$dR = dy/q\mu N' = \frac{dy}{Z\mu_n C[V_{GS}-V_T-V(y)]} , \tag{7.8}$$

where μ_n is the electron mobility, C the gate capacity per unit area, $V_{GS} = V_G - V_S$ the gate to source voltage, V_T the threshold value of V_{GS}, and V(y) the potential the channel at a distance y from the source, or Y-v from the drain. Note that the rectangular bracket in the denominator is a first approximation only, based on the simple capacitor model. In general, as we shall see below, Fermi statistics is applicable, essentially replacing the bracket [ ] by $k_BT\{\exp([\ ]/k_BT) - 1\}$, where k_B is Boltzmann's constant. The quantum 1/f noise in the element of resistance is given by the basic quantum 1/f formula for mobility fluctuations

$$\frac{\langle(\delta dR)^2\rangle_f}{(dR)^2} = \frac{\alpha_o}{f dN} , \tag{7.9}$$

where dN is the number of carriers in the element of resistance

$$dN = ZQ_n dy/q \tag{7.10}$$

and $Q_n = -C(V_{GS}-V_T)$ is the charge per unit area under the gate, while q=-e is the charge of the electron. Using Eq. (7.8) for dR, and (7.10) for dN, we obtain

$$f\langle(\delta dR)^2\rangle_f = [dy/q\mu N']^2\frac{\alpha_o}{fdN} = -\frac{q\alpha_o dy}{\mu_n{}^2 Z^3 C^3[V_{GS}-V_T-V(y)]^3}\ . \tag{7.11}$$

Multiplying on both sides with the channel current

$$I = -dV/dR = -Z\mu_n C[V_{GS}-V_T-V(y)]dV/dy \tag{7.12}$$

and integrating, yields

$$fI\langle(\delta R)^2\rangle_f = \int_0^{V_{DS}} \frac{q\alpha_o dV}{\mu_n Z^2C^2[V_{GS}-V_T-V]^2} = \frac{q\alpha_o}{\mu_n Z^2 C^2}\frac{V_{DS}}{V_G{}^*(V_G{}^*-V_{DS})}\ . \tag{7.13}$$

Here $V_G{}^*=V_{GS}-V_T$. This simple summation of spectra is justified, because both theory and experiment have shown that the fluctuations of the various elements dR are uncorrelated, down to the smallest experimentally accessible lengths, and down to the electronic correlation length. Dividing both sides with IR^2 and replacing V_{DS}/I by R on the r.h.s., we obtain

$$f\frac{\langle(\delta R)^2\rangle_f}{R^2} = \frac{q\alpha_o}{\mu_n Z^2C^2RV_G{}^*(V_G{}^*-V_{DS})} = \frac{q\alpha_o}{ZCV_G{}^*R}\left[\frac{dR}{dy}\right]_D = \frac{q\mu_n\alpha_o}{R}\left[\frac{dR}{dy}\right]_S\left[\frac{dR}{dy}\right]_D, \tag{7.14}$$

where we have used Eq. (7.8) at y=L and V(y) = V_{DS}, the drain potential, to define the drain value $[dR/dy]_D$ of [dR/dy]. At y=0 we have V(y) = 0 and we define there in the same way $[dR/dy]_S$. Note also that multiplication of Eq. (7.12) with dy, followed by integration from 0 to L yields in this approximation, with the stringent limitations mentioned above, the expression of the channel resistance

$$R = (L/Z\mu_n C)/(V_G{}^*-V_{DS}/2) \tag{7.15}$$

that is present in the above equations.

b. Inclusion of Fermi statistics below saturation

Introducing Fermi statistics, for a $GaN/Al_xGa_{1-x}N$ doped n-channel HFET the number of carriers per unit length N' of the 2-dimensional channel is written in the form

$$N' = ZDV_{th}\log\{1+\exp[(V_G{}^*-V)/V_{th}]\}. \tag{7.16}$$

Here $D_{eff}=qm/\pi\hbar$ is q times the effective density of states per unit area. Multiplying Eq. (7.13) by I/f, this yields the spectral density of V_{DS} fluctuations in terms of device width Z, channel current I, and thermal voltage $V_{Th}=kT/q$

$$<(\delta V_{DS})^2>_f = (|I|/fZ^2 D_{eff} qV_{th}) \int_{X_0}^{X_1} (\alpha_H/\mu_n)[dX/(X-1)\ln^2 X]; \qquad (7.17)$$

$$X \equiv 1+\exp(\frac{V_G^* - V}{V_{th}}). \qquad (7.18)$$

Here X_0 and X_1 are the values of X at the source (V=0) and at the drain ($V=V_{DS}$), while $\alpha_H=\alpha_0(y)$ is a y-dependent form of the quantum 1/f coefficient introduced in Eq. (7.7) above. For $(V_G^*-V)/V_{th}<<1$,

$$X-1=(V_G^*-V)/V_{th}, \qquad (7.19$$

and the linear approximation of Eqs. (7.11)-(7.13) is regained for a 2D quantized channel.

Eqs. (7.13)-(7.17) are applicable if no saturation occurs. In general, part of the channel may be sub-threshold. In that case,

$$fI_{Ch} < (\delta R)^2 >_f = \int_0^{V_{sat}} \frac{\alpha_{coh} dV}{q\mu N'^2} + \int_{V_{sat}}^{V_{DS}} \frac{\alpha_{conv} q v_s^2 dV}{q\mu I_{Ch}^2} \approx \frac{\sqrt{2}}{q\mu} \int_0^{V_{DS}} \frac{\alpha_H(N')dV}{I_{Ch}^2/q^2v_s^2 + Z^2 D_{eff}^2 V_{th} \ln\{1+\exp[(V_G^* - V)/V_{th})]\}} \qquad (7.20)$$

Eq. (7.20) includes the field dependence of α and μ, but neglects the impact ionization effect in the subthreshold section of the channel length. Using the fact that the velocity of the carriers shows strong saturation in that section, to include impact ionization effect, we split up the integral at $V(y) = V_{G*}-V_{th}$ and write the corresponding second part of the integral in Eq. (7.20) separately, with the number of carriers per unit channel length defined as $N' = I_{ch}/qv_s$, where v_s is the saturation velocity, and α approximated by its coherent value, α_{coh}. We also can replace the ratio v(E)/E by 3.5 μ_0, where μ_o is the low-field mobility. The last form is an approximation in which the two denominators are added, allowing the larger one to prevail automatically, but keeping α in the general form given by Eq. (7.7). The middle form, with 2 terms, allows us to find a theoretical expression

$$\alpha_{theor} = \frac{I_{ch}L^2}{qV_{DS}^2\mu^2}\{\frac{\alpha_H^{coh} I_{ch}}{qZ^2 D_{eff}^2 V_{th} V_{DS}} + \frac{\alpha_H^{conv} q v_s^2}{I_{ch}}(1-\frac{V_G^*}{V_{DS}}+\frac{V_{th}}{V_{DS}})\} \qquad (7.21)$$

for the experimental Hooge constant defined by $\alpha_{exp} \equiv [S_V/V^2]\, L^2/Re\mu$. R is here the channel resistance and $V_{G*} = V_{GS}-V_T$. The experimental values α_{exp} measured at V_{DS} =5V by Balandin et al. [121], are 4.9, 4.2, 11, 16 and 17, in units of 10^{-5} corresponding to V_{G*} values of 2, 3, 3.45, 4.25 and 5 volts respectively. Eq. (7.3) yields in the same conditions the values α_{exp} shown in Table I and Fig. 3 below. The agreement is good, with no fudge factors.

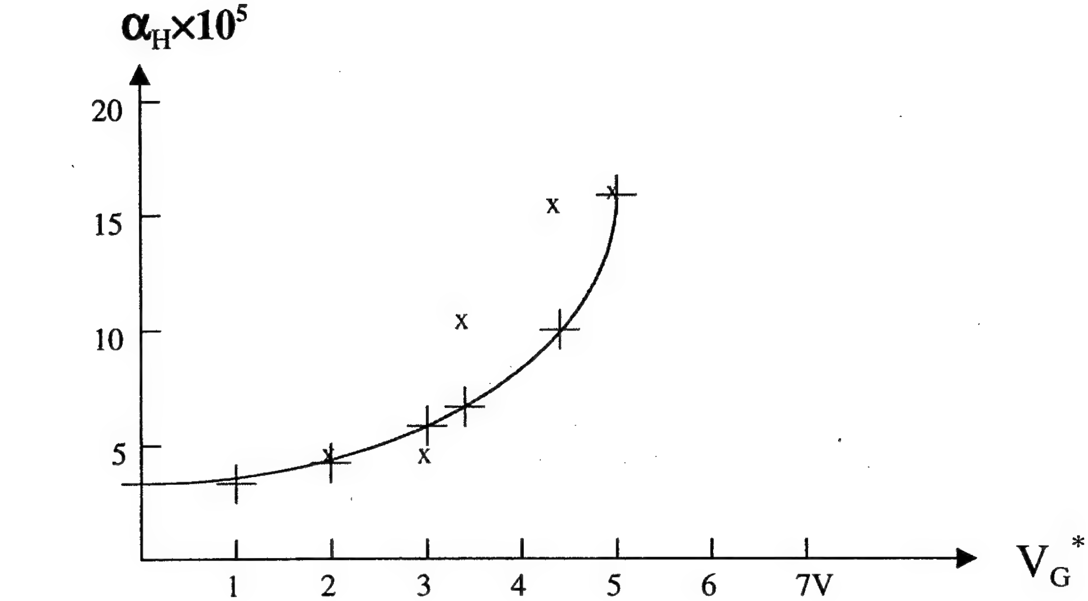

Fig. 3: Comparison of the quantum 1/f first-principles results + with the experimental results x of A. Balandin et al., on "Flicker Noise in GaN/AlGaN Doped Channel Heterostructure FETs", IEEE-Electron Device Letters 19, 475-477 (1998).

TABLE I

	Markers							
$V_G^*/1V$		0	1	2	3	3.45	4.25	5
$I_{DS}/1mA$				1.9	2.55	3.1	3.8	4.9
$\alpha_H^{theor} \cdot 10^5$	+	2.95	3	3.6	5.0	7.0	9.91	16 (Eq. 7.21)
$\alpha_H^{exp} \cdot 10^5$	x			4.9	4.2	11	16.0	17 (Balandin)

$$\alpha_H^{theor} \equiv [S_V/V^2]\, L^2/\mathrm{Re}\mu = \frac{I_{ch}L^2}{qV_{DS}^2\mu^2}\left\{\frac{\alpha_H^{coh} I_{ch}}{qZ^2 D_{eff}^2 V_{th} V_{DS}} + \frac{\alpha_H^{conv} q v_s^2}{I_{ch}}\left(1 - \frac{V_G^*}{V_{DS}} + \frac{V_{th}}{V_{DS}}\right)\right\}$$

$$\equiv \frac{L^2}{1\mu^2} \bullet \left(\frac{92.4\, cm^2/V\cdot s}{\mu_{eff}}\right)^2 \bullet \left(\frac{5V}{V_{DS}}\right)^2 \left\{2.4\cdot 10^{-5}\left(\frac{50\mu}{Z}\right)^2 \frac{5V}{V_{DS}}\left(\frac{I}{1.9mA}\right)^2 + 1.95\cdot 10^{-5}\frac{\alpha_H^{conv}}{4.1\cdot 10^{-6}}\left(\frac{v}{10^7 cm/s}\right)^2\left(1 - \frac{V_G^*}{V_{DS}} + \frac{V_{th}}{V_{DS}}\right)\right\}$$

B8. Phase Noise in RTDs and in Oscillators Based on Them, up to THz Frequencies

8.1 Introduction.

For imaging and remote sensing applications, the phase noise of the THz generator must be minimized. This can be done as part of the optimization process on the basis of a properly chosen figure of merit. For this, the present Report provides an analytical phase noise expression as a function of the device parameters and operation point. The quantum 1/f theory is used to calculate from first principles the 1/f noise present in the device parameters and in the resulting system frequency from resonant tunneling diodes (RTDs), super-electronic lattice devices (SLEDs), Gunn devices (TEDs), and transit time diodes. In general, quantum /f fluctuations in the dissipative elements lead to a Q^{-4} dependence of the spectral density of fractional frequency fluctuations and of the corresponding phase noise, where Q is the quality factor.

Fluctuations with a spectral density proportional to 1/f are found in a large number of systems in science, technology and everyday life. These fluctuations are known as 1/f noise in general. They have first been noticed by Johnson in early amplifiers, have limited the performance of vacuum tubes in the thirties and forties, and have later hampered the introduction of semiconductor devices.

The present Section is focused on the general origin of fundamental 1/f noise as a universal form of chaos, and on the cause of its ubiquity. It starts with a *special case* of the general 1/f noise phenomenon, the Quantum 1/f Effect (with its conventional and coherent contributions) which is as fundamental as time and space. The 1/f fluctuations are a necessary consequence of the mathematical homogeneity of the dynamical (or physical) equations describing the motion of an arbitrary chaotic or stochastic nonlinear system. A sufficient criterion was derived by the author. It indicates if an arbitrary system governed by a given system of nonlinear integro-differential equations will exhibit 1/f noise. The criterion was applied to several particular systems, and is used to predict the fundamental quantum 1/f effect as a *special case*.

8.2. Conventional quantum 1/f effect

This effect[1-6] is present in any cross section or process rate involving charged particles or current carriers. The physical origin of quantum 1/f noise is easy to understand. Consider for example Coulomb scattering of current carriers, e.g., electrons on a center of force. The scattered electrons reaching a detector at a given angle away from the direction of the incident beam are described by DeBroglie waves of a frequency corresponding to their energy. However, some of the electrons have lost energy in the scattering process, due to the emission of bremsstrahlung. Therefore, part of the outgoing DeBroglie waves is shifted to slightly lower frequencies. When we calculate the probability density in the scattered beam, we obtain also cross terms, linear both in the part scattered with and without bremsstrahlung. These cross terms oscillate with the same frequency as the frequency of the emitted bremsstrahlung photons. The emission of photons at all frequencies results therefore in probability density fluctuations at all frequencies. The corresponding current density fluctuations are obtained by multiplying the probability density fluctuations by the velocity of the scattered current carriers. Finally, these current fluctuations present in the scattered beam will be noticed at the detector as low frequency

current fluctuations, and will be interpreted as fundamental cross section fluctuations in the scattering cross section of the scatterer. While incoming carriers may have been Poisson distributed, the scattered beam will exhibit super-Poissonian statistics, or bunching, due to this new effect which we may call quantum 1/f effect. The quantum 1/f effect is thus a many-body or collective effect, at least a two-particle effect, best described through the two-particle wave function and two-particle correlation function.

Let us estimate the magnitude of the quantum 1/f effect semiclassically by starting with the classical (Larmor) formula $2q^2\mathbf{a}^2/3c^3$ for the power radiated by a particle of charge q and acceleration $\mathbf{a}$. The acceleration can be approximated by a delta function $\mathbf{a}(t) = \Delta\mathbf{v}\delta(t)$ whose Fourier transform $\Delta\mathbf{v}$ is constant and is the change in the velocity vector of the particle during the almost instantaneous scattering process. The one-sided spectral density of the emitted bremsstrahlung power $4q^2(\Delta\mathbf{v})^2/3c^3$ is therefore also constant. The number $4q^2(\Delta\mathbf{v})^2/3hfc^3$ of emitted photons per unit frequency interval is obtained by dividing with the energy hf of one photon. The probability amplitude of photon emission $[4q(\Delta\mathbf{v})^2/3hfc^3]^{1/2}e^{i\gamma}$ is given by the square root of this photon number spectrum, including also a phase factor $e^{i\gamma}$. Let ψ be a representative Schrödinger catalogue wave function of the scattered outgoing charged particles, which is a single-particle function, normalized to the actual scattered particle concentration. The beat term in the probability density $\rho=|\psi|^2$ is linear both in this bremsstrahlung amplitude and in the non-bremsstrahlung amplitude. Its spectral density will therefore be given by the product of the squared probability amplitude of photon emission (proportional to 1/f) with the squared non-bremsstrahlung amplitude which is independent of f. The resulting spectral density of fractional probability density fluctuations is obtained by dividing with $|\psi|^4$ and is therefore

$$|\psi|^{-4}S_{|\psi|^2}(f) = 8q^2(\Delta\mathbf{v})^2/3hfNc^3 = \quad 2\alpha A/fN = j^{-2}S_j(f), \tag{8.1}$$

where $\alpha = e^2/\hbar c = 1/137$ is the fine structure constant and $\alpha A = 4q^2(\Delta\mathbf{v})^2/3hc^3$ is known as the infrared exponent in quantum field theory, and is known as quantum 1/f noise co-efficient, or Hooge constant, in electrophysics.

The spectral density of current density fluctuations is obtained by multiplying the probability density fluctuation spectrum with the squared velocity of the outgoing particles. When we calculate the spectral density of fractional fluctuations in the scattered current j, the outgoing velocity simplifies, and therefore Eq. (8.1) also gives the spectrum of current fluctuations $S_j(f)$, as indicated above. The quantum 1/f noise contribution of each carrier is independent, and therefore the quantum 1/f noise from N carriers is N times larger. However, the current j will also be N times larger, and therefore in Eq. (8.1) a factor N was included in the denominator for the case in which the cross section fluctuation is observed on N carriers simultaneously.

The fundamental fluctuations of cross sections and process rates are reflected in various kinetic coefficients in condensed matter, such as the mobility μ and the diffusion constant D, the surface and bulk recombination speeds s, and recombination times τ, the rate of tunneling j_t and the thermal diffusivity in semiconductors. Therefore, the spectral density of fractional fluctuations in all these coefficients is given also by Eq. (8.1).

When we apply Eq. (8.1) to a certain device, we first need to find out which are the cross sections σ or process rates which limit the current I through the device, or which determine any other device parameter P. Second, we have to determine both the velocity change $\Delta\mathbf{v}$ of the

scattered carriers and the number N of carriers simultaneously used to test each of these cross sections or rates. Then Eq. (8.1) provides the spectral density of quantum 1/f cross section or rate fluctuations. These spectral densities are multiplied by the squared partial derivative $(\partial I/\partial\sigma)^2$ of the current, or of the device parameter P of interest, to obtain the spectral density of fractional device noise contributions from the cross sections and rates considered. After doing this with all cross sections and process rates, we add the results and bring (factor out) the fine structure constant α as a common factor in front. This yields excellent agreement with the experiment in a large variety of samples, devices and physical systems.

Eq. (8.1) was derived in second quantization, using the commutation rules for boson field operators. For fermions one repeats the calculation replacing in the derivation the commutators of field operators by anticommutators, which yields[1-6]

$$\rho^{-2}S_\rho(f) = j^{-2}S_j(f) = \sigma^{-2}S_\sigma(f) = 2\alpha A/f(N-1) \tag{8.2}$$

This causes no difficulties, since $N\geq2$ for particle correlations to be defined, and is practically the same as Eq. (8.1), since usually $N>>1$. Eqs. (8.1) and (8.2) suggest a new notion of physical cross sections and process rates which contain 1/f noise, and express a fundamental law of physics, important in most high-technology applications.

We turn now to the connection to the coherent Quantum 1/f Effect, essentially caused by the uncertainty of the electron mass, by the coherent state of the field of the electron. The coherent state has an uncertain energy. The coherent state in a conductor or semiconductor sample is the result of the experimental efforts directed towards establishing a steady and constant current, and is therefore the state defined by the collective motion, i.e. by the drift of the current carriers. It is expressed in the Hamiltonian by the magnetic energy E_m, per unit length, of the current carried by the sample. In very small samples or electronic devices, this magnetic energy

$$E_m = \int(B^2/8\pi)d^3x = [nevS/c]^2\ln(R/r) \tag{8.3}$$

is much smaller than the total kinetic energy E_k of the drift motion of the individual carriers

$$E_k = \sum_i m_i v^2/2 = nSmv^2/2 = E_m/s. \tag{8.4}$$

Here we have introduced the magnetic field B, the carrier concentration n, the cross sectional area S and radius r of the cylindrical sample (e.g., a current carrying wire), the radius R of the electric circuit, and the "coherece ratio"

$$s=E_m/E_k = 2ne^2S/mc^2\ln(R/r) = 2e^2N'/mc^2, \tag{8.5}$$

where $N' = nS$ is the number of carriers per unit length of the sample and the natural logarithm $\ln(R/r)$ has been approximated by one in the last form. We expect the observed spectral density of the mobility fluctuations to be given by a relation of the form

$$(1/\mu^2)S_\mu(f)=[1/(1+s)][2\alpha A/fN] + [s/(1+s)][2\alpha/\pi fN] \tag{8.6}$$

which can be interpreted as an expression of the effective Hooge constant if the number N of carriers in the (homogeneous) sample is brought to the numerator of the left hand side. In this

equation $\alpha A=2\alpha(\Delta v/c)^2/3\pi$ is the usual nonrelativistic expression of the infrared exponent, present in the familiar form of the conventional quantum 1/f effect [1]-[10]. This equation is limited to quantum 1/f mobility (or diffusion) fluctuations, and does not include the quantum 1/f noise in the surface and bulk recombination cross sections, in the surface and bulk trapping centers, in tunneling and injection processes, in emission or in transitions between two solids.

Note that the coherence ratio s introduced here equals the unity for the critical value N' = N" = $2{\cdot}10^{12}$/cm., e.g. for a cross section $S = 2{\cdot}10^{-4}$ cm^2 of the sample when $n = 10^{16}$. For small samples with N'<<N" only the first term survives, while for N'>N" the second term in Eq. (8.6) is dominant.

8.3 1/f Fluctuations in RTDs

Resonant tunneling diodes have been proposed as generators of THz oscillations and radiation. They consist of two potential barriers enclosing a quantum well. Electrons penetrating the potential barriers by tunneling are controlled by the quasistationary energy levels defined by the penetrating the potential barriers by tunneling are controlled by the quasistationary energy levels defined by the potential well. If their energy is close to the first energy level in the well, resonance occurs, and a peak I_P of the current through the diode occurs. This corresponds to an applied bias voltage V_P. If, however, the applied voltage increases further, only a negligibly small non-resonant current trickle remains at the voltage $V=V_V$ and a broad valley is observed in the I/V characteristic. Scattering processes that reduce the energy of the carriers to a value close to eV_P will always be present, generating a finite current minimum I_V at V_V. Between V_P and V_V there is a negative differential conductance

$$G=-(I_P-I_V)/(V_V-V_P) \tag{8.7}$$

on the I/V curve, that is used to generate oscillations. The 1/f noise in I_V is given by Eqs. (8.1)-(8.2) with

$$(\Delta v/c)^2=2eV_V/m. \tag{8.8}$$

Taking for instance $V_P=0.4$ V, $I_P=2.5\ 10^8$A/m^2, $V_V=0.6$ V, $I_V=4\ 10^7$ A/m^2, we obtain with $m_{eff}=0.068\ m_o$,

$$NI_V^{-2}S_{I_v}(f) =2\alpha A/f =7.4/0.068\ 10^{-9} =1.3\ 10^{-7} \tag{8.9}$$

N is given by

$$N =\tau I_V/e, \tag{8.10}$$

where τ is the lifetime of the carriers. With a cross-sectional area of 10^{-6} cm^2 and $\tau=10^{-10}$, we obtain N= 2.5 10^6.

Finally, the quantum 1/f frequency fluctuations can be obtained from the formula

$$S_{\delta\omega/\omega} =(1/4Q^4)S_{\delta G/G} \tag{8.11}$$

which is derived in Sec. V below. This finally yields with Eq. (8.1)

$$S_{\delta\omega/\omega} =(1/4Q^4)(4\alpha/3\pi)(2eV_V/mc^2) \tag{8.12}$$

for the fractional frequency fluctuation spectrum exhibited by the RTD if included in an RF

circuit of quality factor Q.

8.4 Appendix: frequency and phase fluctuations from 1/f noise in dissipation

Resonant systems can be described as a harmonic oscillator with losses

$$dx/dt + \gamma dx/dt + \omega_o^2 x = F(t). \tag{8.13}$$

The quantum 1/f fluctuations are present in the loss coefficient γ. They are given by an expression of the form

$$S_{\delta\gamma/\gamma}(f) = \Lambda/f, \tag{8.14}$$

where Λ is a quantum 1/f coefficient characterizing the elementary loss process.
The resonance frequency is given by

$$\omega_r^2 = \omega_o^2 + \gamma^2. \tag{8.15}$$

The quantum 1/f fluctuations in the resonance frequency are given by $\omega_r\delta\omega_r = -2\gamma\delta\gamma$, or

$$\delta\omega_r/\omega_r = -2(\gamma/\omega_r)^2\delta\gamma/\gamma = -(1/2Q^2)(\delta\gamma/\gamma), \tag{8.16}$$

where $Q=\omega_r/2\gamma$ is the quality factor. Squaring, averaging and particularizing Eq. (8.16) for the unit frequency interval, we obtain the Q^{-4} law

$$S_y(f) = <(\delta\omega_r/\omega_r)^2>_f = (1/4Q^4)<(\delta\gamma/\gamma)^2>_f = \Lambda/4fQ^4, \tag{8.17}$$

where y is the fractional frequency fluctuation $\delta\omega_r/\omega_r$. This law is also applicable to quartz resonators, where it was first introduced [14] in 1978. The phase noise is obtained from

$$S_\phi(f) = (\omega_r/2\pi f)^2 S_y(f), \text{ or } L(f) = (1/2)S_\phi(f). \tag{8.18}$$

two-sided. The examples in the last two sections show how the phase noise is to be found in other solid state sources of THz radiation.

B9. Quantum 1/F Effect in Biological and Chemical Piezoelectric Sensors

Piezoelectric sensors used for the detection of chemical agents and for electronic nose instruments are based on BAW and SAW resonators. They are also useful in the detection of biological agents, and can be specific, particularly if the sensitive surface is activated with the right antigen.

The BAW resonators are used for instance in the "quartz crystal microbalance" (QCM). This is usually a polymer-coated resonating quartz disk, a few mm in diameter, with smaller diameter metal electrodes on each side and with quality factor Q. The resonance frequency is usually in

the 10-30 MHz range. Absorption of gas molecules with mass δm on the surface of the polymer coating gets detected by a reduction of the resonance frequency of the quartz disk, subject also to fundamental quantum 1/f frequency fluctuations. The quantum 1/f limit of detection is given by the quantum 1/f formula for quartz resonators. To optimize the device we must avoid closeness of the crystal volume to the phonon coherence length which corresponds to the maximum error and minimal sensitivity situation. Differential measurements that include a reference resonator without polymer coating can effectively eliminate temperature fluctuations, power suply instability, etc. Adsorbed masses below the pg range can be detected.

Similarily, SAW resonators are used at about ten times higher frequencies in small sensors that operate best with sizes larger than the phonon coherence length. The discussion is similar, but applied to the surface and surface waves.

9.1. Introduction: application of the conventional quantum 1/f effect, a new aspect of quantum mechanics

According to the quantum 1/f effect, quantum-mechanical cross sections σ_0 and process rates Γ_0 are considered to be just the expectation values of the physical quantities σ and Γ, that also contain the quantum 1/f fluctuations. Therefore,

$$S_{\delta\sigma/\sigma}(f) = S_{\delta\Gamma/\Gamma}(f) = (4\alpha/3\pi f)(\Delta v/c)^2 = 4\alpha(\Delta \dot{\mathbf{P}})^2/3\pi f e^2 c^2 \qquad (9.1)$$

Here $\alpha = (1/4\pi\varepsilon_0)(2\pi e^2/hc) = 1/137$ is Sommerfeld's fine structure constant, a dimensionless universal constant constructed from Planck's constant, the charge e of the electron, and the speed of light c

Phonon scattering in the resonator crystal was long suspected to limit the short- and medium-term frequency stability in all crystal resonators [124]. Phonon scattering can occur on other phonons (particularly at higher temperatures) or on crystal defects (favored by default at low temperatures). In both cases this process is shown to yield a 1/f spectrum of resonator frequency fluctuations through the conventional Quantum 1/f Effect. As was first shown on this basis with the help of a simple harmonic oscillator model [14], bulk acoustic wave (BAW) and surface acoustic wave (SAW) quartz resonators ought to have a Q^{-4} dependence of their FM power spectrum. This has been experimentally verified by Gagnepain and Uebersfeld for BAW resonators [36] when they noticed their $1/Q^{4.4}$ law, and by Parker for the SAW case [37]. Although the quantum 1/f effect provided the historical basis for the derivation of the Q^{-4} law [14] as being caused by fluctuations in the dissipation rate of the quartz resonator, the exact mechanism through which the quantum 1/f effect modulates the dissipation rate remained unknown from 1978 to 1991.

Finally, the bridge directly connecting 1/f noise in frequency standards to the quantum 1/f effect was discovered [38]-[40], yielding simple quantum 1/f engineering formulas. ***In the present Section, this thorough understanding and knowledge is used to calculate the fundamental sensitivity limits of quartz resonator sensors used for the detection of biological and chemical agents.***

Here is how it works. The rate Γ of phonon-interactions which remove phonons from the main quartz sensor's resonator mode is modulated by the quantum 1/f effect, therefore exhibiting observable (macroscopic) quantum fluctuations, while its expectation value remains constant. Indeed, whenever a phonon is removed from the main resonator mode, the time-derivative of the polarization vector of the quartz crystal $d\mathbf{P}/dt=\dot{\mathbf{P}}$ is suddenly affected, suffering a step-like modification as a function of time. From Maxwell's equations we know, however, that $\dot{\mathbf{P}}$ is added to the current J and that such a modification of the current causes radiation. Solving Maxwell's equations we find that as a result of the phonon removal there is a constant energy of $(1/4\pi\varepsilon_0)^4(\Delta\dot{\mathbf{P}})^2/3c^3$ radiated away per unit frequency, interval, i.e. per Hertz at any frequency f. Dividing this result by the energy of a photon hf, we find that there is thus a probability of $2\alpha(\Delta\dot{\mathbf{P}})^2/3\pi fe^2c^2$ for the emission (radiation) of a bremsstrahlung photon of frequency f. SI units are used here, while Gaussian units were used in [40].

Since there is a probability of $2\alpha(\Delta\dot{\mathbf{P}})^2/3\pi fe^2c^2 << 1$ for the emission of a bremsstrahlung photon of frequency f, the Quartz crystal suffers a reaction, or a recoil in its quantum state. This causes the phonon-emission rate Γ to perform quantum oscillations with frequency f and with two-sided spectral density S' of fractional fluctuations given by the same expression, $S'_{\delta\Gamma/\Gamma}(f) = 2\alpha(\Delta\dot{\mathbf{P}})^2/3\pi fe^2c^2$. This is here the expression of the quantum 1/f effect. The one-sided spectrum is thus, as was mentioned in the last form of Eq. (9.1)

$$S_{\delta\Gamma/\Gamma}(f) = 4\alpha(\Delta\dot{\mathbf{P}})^2/3\pi fe^2c^2. \tag{9.2}$$

This means that any radiation caused or implied by a quantum transition from one state to another comes with a price. It reacts back on the system, causing the rate of that transition to be modulated by exhibiting observable macroscopic quantum fluctuations. These have a spectral density of fractional rate fluctuations identical to the photon-emission probability accompanying the transition considered. No knowledge of quantum mechanics is therefore needed in order to apply the quantum 1/f effect, One has to divide the energy radiated by the energy hf of one photon of frequency f. This is based just the reality of Planck's constant h and Planck's relation between photon energy and frequency. Knowledge of electrodynamics is needed, however, in order to calculate the energy radiated in a transition.

The reader interested in a basic understanding of the quantum 1/f effect will find a most accessible description at the end of p. 8 and beginning of p. 9 in [54]. That description considers scattering of electrons as an example of transition which emits radiation and suffers a quantum 1/f modulation of its rate, rather than considering scattering of phonons, which, as we believe, is most important in crystal resonators. All that is involved in that derivation is the notion of DeBroglie wave associated to a particle, or the notion of wave function. Old quantum mechanics notions are thus sufficient for a basic understanding of the recoil, or energy-loss mechanism, of the quantum 1/f effect (Q1/fE). For a practical application of the Q1/fE, however, classical physics is sufficient.

9.2. Quartz crystal microbalances

Piezoelectric sensors are:

--Used for the detection of chemical agents and for electronic nose instruments; based on BAW and SAW resonators.

--Useful in the detection of biological agents, and can be specific, particularly if the sensitive surface is activated through deposition of a layer of the right specific antigen, that "attracts" a certain bacterium, microbe, or virus. The antigens are produced by organisms in order to fight, or bind, the pathogenic agents mentioned here.

Piezoelectric sensors are of 2 kinds: bulk acoustic wave (BAW) resonators-based, and surface acoustic wave (SAW) resonator based. The former are used for instance in the "quartz crystal microbalance" (QCM). This is usually a polymer-coated resonating quartz disk, a few mm in diameter, with smaller diameter metal electrodes on each side and with quality factor Q. Their resonance frequency is usually in the 10-30 MHz range, and 10 times higher for SAWs.

These sensors are based on the adsorption of many gas molecules (with total mass δm) on the surface of the polymer coating. This gets detected by a reduction

$$y=\delta\nu/\nu=-\kappa\delta m/m \tag{9.3}$$

of the resonance frequency of the quartz disk. However, the latter is also subject to fundamental frequency fluctuations. Here κ is a constant of proportionality. The quantum 1/f limit of detection is given by

$$\kappa^2 S_{\delta m/m}(f)=S_y(f), \tag{9.4}$$

where $S_y(f)$ is given by formulas [14], [38]-[40], [54]

$$S_y(f) = \beta' V/fQ^4, \text{ for } V\leq\varepsilon^3, \tag{9.5}$$

and

$$S(f) = \beta'\varepsilon^6/fVQ^4, \text{ for } V\geq\varepsilon^3, \tag{9.6}$$

as we show below. Here ε^3 is the phonon coherence volume, first introduced empirically by T. Parker et. al. as a noise coherence volume.

To optimize the device we must avoid closeness of V with ε which corresponds to the maximum error and minimal sensitivity situation. (See the general graph in Fig. 4 below)

To reduce the measurement errors,one uses differential measurements, that include a reference resonator without polymer coating and subtract its frequency changes. This can effectively eliminate the destabilizing effect of temperature fluctuations, power supply instability, etc. This way, adsorbed masses below the pg=10^{12}g range can be detected.

<u>Calculation of the Quantum 1/f Sensitivity Limit</u>

With $<\omega>=10^3$/s being the average circular frequency of a thermal phonon interacting with phonons in the main resonator mode, with $n=kT/<\omega>\hbar$ being the average number of phonons in that typical thermal phonon mode, and with T=300K, we obtain approximately for

the quantum 1/f noise coefficient β' in Eqs 5-6 (see below)

$$\beta' = (N/V)\alpha\hbar\langle\omega\rangle/12n\pi g^2mc^2 = (1/137)(10^{-27}\ 10^8)^2/12kT\pi 10^{-27}9\cdot 10^{20}=1. \qquad (9.7)$$

For $V<\varepsilon^3$, his is in good agreement with the known data for quartz resonators of very high Q as experimental results obtained by F.L. Walls et al., T. Parker et al., J.R. Vig et al., as well as other research groups indicate. Here m is the reduced mass of the elementary oscillating dipoles, N their number in the quartz resonator volume, and g a polarization constant of the order of the unity.

9.3. Saw sensors.

The same way, SAW resonators are used at about higher frequencies in sensors that operate in the $V>\varepsilon^3$ regime. The discussion is similar, but applied to the surface and surface acoustic waves. In that case the coherence length of the phonons is smaller than the crystal size, and therefore we expect several incoherent noise contributions from various regions of the crystal.

a. Spatial incoherence of phonon loss rate fluctuations in low and intermediate Q resonators.
Considering the $\nu=V/\varepsilon^3$ independently fluctuating regions similar, we replace Eq. (8.1) by

$$S_{\delta\Gamma/\Gamma}(f)=\sum_{i=1}^{\nu}\langle(\delta\Gamma_i/\Gamma)^2\rangle_f \quad = \nu^{-1}\langle(\delta\Gamma_i/\Gamma_i)^2\rangle_f = 4\alpha(\Delta\dot{\mathbf{P}}_i)^2/3\pi f\nu e^2c^2. \qquad (9.8)$$

Here we assumed that $\Gamma=\nu\Gamma_i$ and that $\langle(\delta\Gamma_i/\Gamma_i)^2\rangle_f = \nu S_{\delta\Gamma/\Gamma}(f)$ is independent of i. With $\nu=V/\varepsilon$ we finally obtain

$$S_{\delta\Gamma/\Gamma}(f) = 4\alpha\varepsilon^3(\Delta\dot{\mathbf{P}}_i)^2/3\pi fVe^2c^2 = 4\alpha\varepsilon^2(\Delta\dot{\mathbf{P}}_i)^2/3\pi fAe^2c^2. \qquad (9.9)$$

Note that the phonon mean free path is about 40 Å for bulk wave phonons in quartz at room temperature and 500 Å at liquid nitrogen temperatures. This approximates the phonon coherence length ε very well. For SAW phonons the corresponding coherence length values may be 4 times lower due to the smaller velocity of the surface wave and due to its stronger scattering. The wave is localized within about two coherence lengths ε from the surface. Therefore, in the incoherent regime $V = 2\varepsilon A$ is a good approximation. Consequently, we expect an increase of $S_{\delta\omega/\omega}(f)$ proportional with 1/A when the resonant area A is decreased, down to very small areas of the order of ε^2.
b. Coherent Case of High-Q Resonators

From Eq. (9.2) we obtain

$$S_{\delta\Gamma/\Gamma}(f) = 4\alpha(\Delta\dot{\mathbf{P}})^2/3\pi fe^2c^2; \qquad (9.10)$$

The vibrational energy of the crystal can be written in the form

$$W = n\hbar\langle\omega\rangle = 2(Nm/2)(dx/dt)^2 = (Nm/e^2)(edx/dt)^2 = (m/Ne^2)\varepsilon^2(\dot{\mathbf{P}}_i)^2; \qquad (9.12)$$

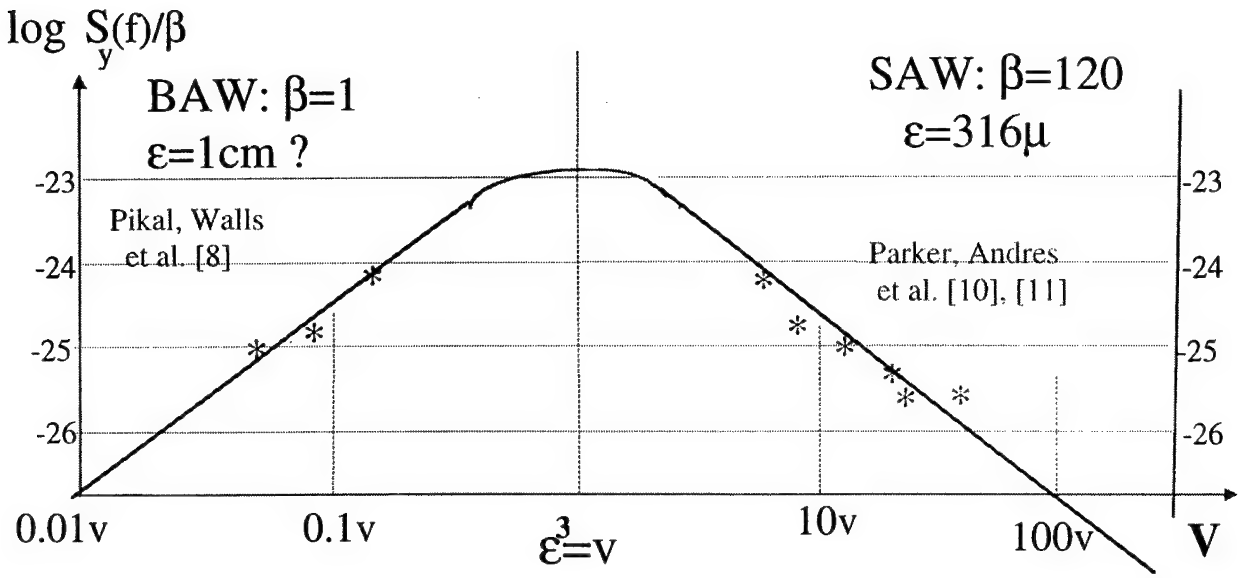

Fig. 4: Quantum 1/f Noise in BAW & SAW Resonators Yields Bio/Chem Sensitivity Limit

The factor two includes the potential energy contribution. Here m is the reduced mass of the elementary oscillating dipoles, e their charge, g a polarization constant of the order of the unity, and N their number in the resonator. Applying a variation $\Delta n=1$ we get

$$\Delta n/n = 2|\Delta\dot{\mathbf{P}}|/|\dot{\mathbf{P}}|, \text{ or } \Delta\dot{\mathbf{P}} = \dot{\mathbf{P}}/2n. \tag{9.13}$$

Solving Eq. (9.12) for $\dot{\mathbf{P}}$ and substituting into (9.13), we obtain

$$|\Delta\dot{\mathbf{P}}| = (N\hbar\langle\omega\rangle/n)^{1/2}(e/2g). \tag{9.14}$$

Substituting $\Delta\dot{\mathbf{P}}$ into Eq. (9.2), we get

$$\Gamma^{-2}S_{\Gamma}(f)=N\alpha\hbar\langle\omega\rangle/3n\pi mc^2fg^2\equiv\Lambda/f. \tag{9.15}$$

Using the harmonic oscillator relation

$$\omega^2 = \omega_o^2 - 2\Gamma^2, \quad \omega\delta\omega = -2\Gamma\delta\Gamma; \tag{9.16}$$

between resonance frequency ω and dissipation Γ, we obtain

$$S_{\delta\omega/\omega}(f) = (1/4Q^4)S_{\delta\gamma/\gamma}(f) = (1/4Q^4)(\Lambda/f) = N\alpha\hbar\langle\omega\rangle/12n\pi mc^2fg^2Q^4; \tag{9.17}$$

$$S(f) = \beta' V/fQ^4, \text{ for } V\leq\varepsilon^3, \tag{9.18}$$

and

$$S(f) = \beta'\varepsilon^6/fVQ^4, \text{ for } V\geq\varepsilon^3, \tag{9.19}$$

As was stated in Eqs. (9.5)-(9.6) above. Here, with an intermediary value $\langle\omega\rangle=10^8$/s, with $n=kT/\hbar\langle\omega\rangle$, T=300K and $kT=4\cdot10^{-21}$ J, we get

$$\beta' =(N/V)\alpha\hbar\langle\omega\rangle/12n\pi g^2mc^2 =10^{22}(1/137)(10^{-27}10^8)^2/12kT\pi10^{-27}\,9\,10^{20} =1. \tag{9.20}$$

as stated above in Eq. (9.7).

c. The Case of Defect Scattering: a two-phonon process.

A phonon from the main resonator mode scatters on a defect and a phonon of comparable frequency emerges into another mode with much smaller phonon occupation number $n_\omega=kT/\hbar\omega$. In this case we have to replace $\langle\omega\rangle$ by ω and $n_{\langle\omega\rangle}$ with n_ω, which gives a β-value which is $(\langle\omega\rangle/\omega)^2$ smaller, i.e. 10^4-10^6 times smaller.

d. The General Case

With $\Gamma=\Gamma' + \Gamma''$, we obtain for the combined phonon and defect scattering case, in general,

$$\beta=\beta'[\Gamma'^2 + (\langle\omega\rangle/\omega)^2\Gamma''^2]/\Gamma^2. \tag{9.21}$$

Although the defect scattering term is small at room temperature, it may become dominant at low temperatures, when the phonon scattering rate Γ' becomes much smaller than the defect scattering rate Γ''.

Since the 1/f noise level depends on the active volume, in the coherent regime one should use the lowest overtone and smallest diameter consistent with other circuit parameters. In the incoherent (low Q) case the opposite should be considered.

9.4. Silicon MEMS resonator sensors

The classical forms of noise present in the frequency of microelectromechanical systems (MEMS) resonators, have been recently investigated and described in detail [123]. The present Section extends this investigation to 1/f noise. That is of fundamental nature in MEMS resonators, and is given by the universal quantum 1/f effect, with some similarities to the case of quartz resonators. When the environmental fluctuations are reduced, e.g., by temperature stabilization, elimination of molecular adsorption, etc., the fundamental limitation introduced by the quantum 1/f effect becomes visible as a flicker floor in the time-domain noise representation. Being ultimately based on Heisenberg's uncertainty relations, this effect defines the quantum limit achievable at low frequencies, when the classical sources of noise have been sufficiently reduced.

The quantum 1/f effect manifests itself in MEMS resonators through conventional quantum 1/f noise. This is a quantum fluctuation present in the quantum mechanical notion of "physical cross section" σ and "physical process rate" Γ, caused by the reaction of the electromagnetic field on the charged particle that emitted it, or in general, on the system that emitted it. It is given by the spectral density of fractional fluctuations, as in Eq. (8.1),

$$S_{\delta\sigma/\sigma}(f) = S_{\delta\Gamma/\Gamma}(f) = (4\alpha/3\pi f)(\Delta v/c)^2, \tag{9.22}$$

where $\Delta\mathbf{v}$ is the velocity vector change of the current carriers of charge e. As shown in the case of BAW and SAW quartz resonators, of ferroelectrics and of antennas, the rate Γ of interest for the calculation of 1/f resonance frequency fluctuations in Si MEMS is the rate of phonon removal from the main mechanical oscillation mode of the oscillating bar. As in the above-mentioned cases, our mechanism of quantum 1/f noise generation is based on bremsstrahlung from electric or magnetic dipoles, rather than from scattering of individual carriers.

The MEMS resonators are shaped as a bar of micro- or nanometric dimensions incased (fixed) at both ends, and subject to bending strain. They are driven by an AC current I flowing in a very thin straight wire attached along the bar, in the presence of a strong constant magnetic field **B**, perpendicular to it. Alternatively, they could be driven electrostatically, or capacitively, by using the wire, or a metallic thin sheet deposited along that side of the bar, as one of the two "plates" of a capacitor. An AC voltage would then be applied to the capacitor at the resonance frequency. Note that in fact there is nothing resembling a bar in the actual MEMS devices. In practice there are comb resonators, “free-free” resonators, and probably others too (J. Vig., private communication). Details are found, e.g., in Clark Nguyen’s publications, [126]-[131]. For simplicity, we continue to refer here to the idealized case of a bar, using effective dimensions that correspond to the actual geometry at hand.

The approach developed for the case of resonators based on quartz and other

piezoelectric substances can not be applied to Si MEMS resonators, because silicon is not piezoelectric. It could only be applied to piezoelectric MEMS resonators, using, for instance, quartz. We therefore develop a new approach in this paper, applicable to the new, driven MEMS resonators. We consider below both the case of magnetic excitation and the capacitive case.

A. Magnetic Excitation of a Resonant Silicon MEMS Bar

The elementary act of dissipation is the absorption of one phonon from the main resonator mode. This can happen either through three photon processes, dominant at higher temperatures, or through two processes, dominant at low temperatures, in the presence of crystal defects of various types. In both cases this elementary act has a spontaneous "bremsstrahlung photon emission (probability) amplitude" associated with it, because it causes a sudden reduction $\Delta\dot{\mathbf{m}}$ of the rate $d\mathbf{m}/dt \equiv \dot{\mathbf{m}}$ of change of the magnetic dipole moment of the system. The system is defined here to include the current carrying circuit, the applied magnetic field **B** with the agency generating it, plus the oscillating bar, i.e., the MEMS. The rate $\dot{\mathbf{m}}$ of change of the magnetic dipole moment of the system is caused by bending oscillations of the bar with the current-carrying wire attached to its side, cutting the lines of force of **B** while it moves.

The conventional quantum 1/f noise in the rate of dissipation Γ is obtained in the CGS Gaussian system by simply replacing the current change $e\Delta\mathbf{v}$ with $\Delta\dot{\mathbf{m}}$

$$S_{\delta\Gamma/\Gamma}(f) = (4\alpha/3\pi f)(\Delta\dot{\mathbf{m}}/ec)^2. \qquad (9.23)$$

To calculate the change $\Delta\dot{\mathbf{m}}$, we note that $(\dot{\mathbf{m}})^2$ is proportional to the transversal vibration speed of the bar and to the total mechanical energy $W=(n+1/2)\hbar\omega$ in the main oscillation mode of the resonator,

$$(n+1/2)\hbar\omega = \kappa(\dot{\mathbf{m}})^2/2. \qquad (9.24)$$

Here κ is a coefficient of proportionality easy to calculate. When a phonon is removed from the main MEMS resonator mode, the energy in Eq. (9.24) is reduced by the amount

$$\hbar\omega = \kappa\dot{\mathbf{m}}\,\Delta\dot{\mathbf{m}}\ . \qquad (9.25)$$

This yields

$$(\Delta\dot{\mathbf{m}})^2 = (\hbar\omega/\kappa\dot{\mathbf{m}})^2 = \hbar\omega/(2n+1)\kappa. \qquad (9.26)$$

Eq. (9.23) becomes now

$$S_{\delta\Gamma/\Gamma}(f) = (4\alpha/3\pi f)\hbar\omega/(2n+1)\kappa(ec)^2 = \underline{4\omega/3\pi f(2n+1)\kappa c^3} = 2\hbar\omega^2/3\pi fW\kappa c^3. \qquad (9.27)$$

This quantum 1/f noise, proportional to the resonance frequency and inversely proportional to the

number of quanta in the main oscillation mode, decreases when the energy in the main resonator mode increases. This is characteristic of quantum mechanical spontaneous emission noise in general. With $\omega=10^{10}$rad/sec and W=0.01 erg we obtain about $10^{-27}/f\kappa$.

To estimate the coefficient κ, we write the mechanical energy, including both the equally contributing kinetic and elastic components, in the form

$$W = M_{eff}v^2/2, \tag{9.28}$$

where M_{eff} is a mass close to the mass M of the bar. Noting that the rate of change in the magnetic moment of the system, caused by the motion of the bar of length L with speed v, is

$$\dot{\mathbf{m}} = \mathbf{n}SdI/dt + \mathbf{n}IdS/dt = \mathbf{n}SBLv/c\mathrm{L} = \mathbf{n}SBLvc/2\int \ln(R/a_s)ds, \tag{9.29}$$

we find

$$\kappa = M_{eff}v^2/\dot{\mathbf{m}}^2 = M_{eff}[c\mathrm{L}/SBL]^2. \tag{9.30}$$

Here we introduced the area S and the inductance L of the AC circuit. We also introduced the approximate expression of L in terms of an integral around the whole circuit. It involves the radius a_s of the cross section of the electric wire used for the AC circuit, as a function of the length parameter s along the wire. We neglected the term with IdS/dt, because $S\omega >> Lv$. We can approximate $S/2\int \ln(R/a_s)ds$ with $R/\langle \ln(R/a_s) \rangle$, where $R=S/l$ is the circuit area S divided by its length l. This way we obtain, e.g., $R'=S/2\int \ln(R/a_s)ds$ = 300 cm as an order of magnitude, and $c/R'=10^8$Hz. With these notations and approximations Eq. (9.30) becomes

$$\kappa = M_{eff}[c/R'BL]^2. \tag{9.31}$$

With $M_{eff}=10^{-11}$g, $L=10^{-3}$cm and $B=10^4$Gauss, we obtain $\kappa=10^3$cm^{-1}. Substituting into Eq. (9.6), we obtain

$$S_{\delta\Gamma/\Gamma}(f) = (4\alpha/3\pi f)(R'BL)^2 \hbar\omega/(2n+1)M_{eff}e^2c^4 = \underline{4(R'BL)}^2\underline{\omega/3\pi f(2n+1)}M_{eff}\underline{c}^5$$
$$= 2(R'BL)^2 \hbar\omega^2/3\pi f W M_{eff}c^5. \tag{9.32}$$

For instance, with the above numerical example, with $\omega=10^{11}$s^{-1}, and with $W=10^{-8}$ erg, we obtain $10^{-22}/f$.

B. Electrostatic Excitation of a Resonant Silicon Bar

The elementary act of dissipation is again the absorption of one phonon from the main resonator mode. This time, the quantum 1/f noise is caused by the sudden change in the rate of change of the dipole moment $\dot{\mathbf{p}}$ of the capacitor, when the phonon is absorbed. Replacing the current change $e\Delta\mathbf{v}$ this time with $\Delta\dot{\mathbf{p}}$, we obtain

$$S_{\delta\Gamma/\Gamma}(f) = 4\alpha(\Delta\dot{\mathbf{p}})^2/3\pi f e^2c^2. \tag{9.33}$$

To calculate the change $\Delta\dot{\mathbf{p}}$, we note that $(\dot{\mathbf{p}})^2$ is proportional to the transversal vibration speed of the bar and to the total mechanical energy $W=(n+1/2)\hbar\omega$ in the main oscillation mode of the resonator,

$$(n+1/2)\hbar\omega = \kappa'(\dot{\mathbf{p}})^2/2. \qquad (9.34)$$

Here κ' is a coefficient of proportionality easy to calculate. When a phonon is removed from the main MEMS resonator mode, the energy in Eq. (9.34) is reduced by the amount

$$\hbar\omega = \kappa'\dot{\mathbf{p}}\,\Delta\dot{\mathbf{p}}\,. \qquad (9.35)$$

This yields

$$(\Delta\dot{\mathbf{p}})^2 = (\hbar\omega/\kappa'\dot{\mathbf{p}})^2 = \hbar\omega/(2n+1)\kappa'. \qquad (9.36)$$

Eq. (9.32) becomes now

$$S_{\delta\Gamma/\Gamma}(f) = (4\alpha/3\pi f)\,\hbar\omega/(2n+1)\kappa'(ec)^2 = \underline{4\omega/3\pi f(2n+1)\kappa'c^3} = 2\hbar\omega^2/3\pi fW\kappa'c^3. \qquad (9.37)$$

This quantum 1/f noise, proportional to the resonance frequency and inversely proportional to the number of quanta in the main oscillation mode, decreases when the energy in the main resonator mode increases. This is characteristic of quantum mechanical spontaneous emission noise in general. With $\omega=10^{11}$rad/sec and $W=10^{-8}$ erg we obtain about $10^{-19}/f\kappa'$.

To estimate the coefficient κ', we write again the mechanical energy in the form

$$W = M_{eff}v^2/2. \qquad (9.38)$$

Noting that the rate of change in the electric dipole moment of the system, caused by the motion of the bar of linear charge density q is

$$\dot{\mathbf{p}} = qLv, \qquad (9.39)$$

we find

$$\kappa' = M_{eff}v^2/\dot{\mathbf{p}}^2 = M_{eff}/q^2L^2. \qquad (9.40)$$

With Meff$=10^{-11}$g, $L=10^{-3}$cm and $q=0.6$ esu/cm, we obtain $\kappa'=2.7\cdot10^{-5}s^2cm^{-3}$. Substituting into Eq. (9.15), we obtain

$$S_{\delta\Gamma/\Gamma}(f) = (4\alpha/3\pi f)q^2L^2\hbar\omega/(2n+1)M_{eff}(ec)^2 = \underline{4q^2L^2\omega/3\pi f(2n+1)M_{eff}c^3}$$
$$= 2q^2L^2\hbar\omega^2/3\pi fWM_{eff}c^3. \qquad (9.41)$$

For instance, with the above numerical example, with $\omega=10^{11}s^{-1}$, and with $W=10^{-8}$ erg, we obtain $3.6\cdot10^{-15}/f$.

Finally, the quantum 1/f frequency fluctuations can be obtained from the formula

$$S_{\delta\omega/\omega} = (1/4Q^4)S_{\delta\Gamma/\Gamma} \qquad (9.42)$$

which is derived in Sec. IV below. This finally yields with Eq. (9.41)

$$S_{\delta\omega/\omega} = (1/2Q^4)q^2L^2\hbar\omega^2/3\pi fWM_{eff}c^3. \tag{9.43}$$

for the electrostatic capacitively coupled case, and, from Eq. (9.31),

$$S_{\delta\omega/\omega} = (1/2Q^4)(R'BL)^2\hbar\omega^2/3\pi fWM_{eff}c^5 \tag{9.44}$$

for the fractional frequency fluctuation spectrum exhibited by the magnetically driven MEMS resonator. The numerical estimated show that the electrostatically driven resonator is much noisier than the magnetically driven one, when it comes to 1/f noise. This is because the magnetic dipole radiation is much weaker, being of higher order than the electric dipole radiation.

9.5. Conclusions

1- The quantum 1/f limit of BAW and SAW QCMs is given by simple formulas allowing calculation of the ultimate mass and concentration threshold of detection.
2- The devices are optimized by avoiding the $V=\varepsilon^3$ region.
3- The magnetic excitation sensors based on MEMS resonators have a lower 1/f noise limit. Than the electrostatically excited ones.
4- The quantum 1/f theory and engineering formulas developed here allow for the optimization of the design and implementation of novel, completely monolithic integrated MEMS resonators and sensors.

The author thanks Dr. J.R. Vig for suggesting the MEMS 1/f problem and for his advice in many ways.

B10. Coherent Quantum 1/f Effect In Cavity Resonators

Electromagnetic Helmholtz Resonators are oscillant systems that also include dissipative elements. If they are oscillating in a well defined mode, they are described by a simple harmonic oscillator equation with dissipative coefficient γ and resonance frequency $\omega_r=2\pi\nu_r$

$$\omega_r^2 = \omega_0^2 + \gamma^2. \tag{10.1}$$

Differentiating this expression, and dividing by $2\omega_r^2$, we get the spectral density of fractional fluctuations

$$S_{\delta\omega/\omega} = (1/4Q^4)S_{\Delta\gamma/\gamma}. \tag{10.2}$$

The physical current density j, and the resistivity ρ, must exhibit fundamental quantum 1/f noise [125] given by

$$S_{\delta j/j}(f) = S_{\delta\rho/\rho}(f) = \Lambda/f, \quad \text{with} \quad \underline{\Lambda = 2\alpha/\pi N}. \tag{10.3}$$

Here α is the fine structure constant. This is the coherent quantum 1/f effect [125] that is applicable, because the number of carriers in any "salami slice" is not smaller than 1. That slice is defined to be perpendicular to the direction of the current density vector in the wall of the resonator. Its thickness equals twice the classical radius of the electron $e^2/mc^2 = 2.8 \cdot 10^{-13}$ cm.

The spectral density of fractional fluctuations is thus the same for the conductivity σ and electron mobility μ in the resonator walls of area A enclosing the volume V. The coherent quantum 1/f formula was used for the quantum 1/f coefficient Λ. Using $N \approx n_0 A\delta$, for the effective number of carriers that is defining the notion of current, of γ, σ and μ, with $n_0 = N/V$, and a well-known expression

$$Q = kV/A\delta = \omega/2\gamma; \tag{10.4}$$

($k \approx 1$ is geometrical factor) of the quality factor Q in terms of the penetration depth δ, we get the spectral density of fractional fluctuations

$$S_{\delta\nu/\nu} = \alpha/2\pi f k Q^3 V n_0. \tag{10.5}$$

For instance, with ν=100GHz, $Q=10^4$, $V=0.03\ cm^3$, and $n_0 = 5 \cdot 10^{22}\ cm^{-3}$ we obtain $S_{\delta\nu/\nu} \approx 10^{-36}/f$. This is a rather small quantum limit that may be hard to observe due to other fluctuations present, unless f is very small.

B11. Generalization of the Leeson Formula

The phase noise $L(f_m)$ of oscillators is described by the empirical Leeson formula [132], with a second term that was introduced by the author based on the quantum 1/f theory [14] under this Grant:

$$L(f_m) = 10\log\left[\frac{1}{2}\left(\left(\frac{f_0}{2Q_l f_m}\right)^2 + 1\right)\left(\frac{f_c}{f_m} + 1\right)\left(\frac{FkT}{P_s}\right) + \frac{f_0^2}{2f_m^2}\frac{1}{4Q_l^4}S_{\delta\gamma/\gamma}\right] \quad \text{(L-H Formula)} \tag{11.1}$$

Here Q_l is the loaded quality factor, f_0 is the resonance frequency, f_c is the flicker corner frequency of the device generating the oscillations, γ is the dissipation rate that causes the osillator's free oscillations to attenuate, and $S_{\delta\gamma/\gamma}$ is the spectral density of fractional fluctuations in the dissipation rate γ. P_s is the amplifier's input signal power, and F is its noise figure. The bracket [ ] in Eq. (11.1) is $S_\phi/2$. This generalization represents a major breakthrough of wide scientific and technical application, that has been realized only recently, and that is formulated here for the first time in this form. This is the basis of our ultra-low phase noise effort in MURI #17/2001.

When he met the present author/PI at the 2001 Frequency Control Symposium in Seattle in June 2001, David B. Leeson enthusiastically embraced this generalization (Leeson: private communication). It is particularly important for high-tech, high-stability oscillators that are close to their quantum limit. It contributes the most important term in that case.

In modern military communication, radar and electronic warfare (EW) systems, the complex frequency, bandwidth and signal-to-noise (S/N) ratio requirements make the direct conversion (or homodyne) transceiver architecture superior to the traditional heterodyne RF transceiver-based approach. However, because it converts signals directly to (or from) the baseband, the direct conversion transceiver demands integrated circuits (and/or semiconductor devices) with *extremely low 1/f noise*. Additionally, because the gain provided by the LNA and the mixer is limited, the down converted signal is very sensitive to 1/f noise of the LNAs, filters

and mixers. For example, the 95S-1 direct conversion radio produced by Rockwell Collins covers input channels from 30KHz to 2GHz and requires an extremely low noise skirt (-140 dBc/Hz) near the baseband. The direct transceiver performance is also strongly affected by the noise performance and/or the spurs-free-dynamic-range (SFDR) of the subsequent analog-to-digital (ADC) and digital-to-analog (DACs) converters, especially when the analog-digital interface is placed close to the sensor/antenna for utilizing advanced DSP technologies. To meet the signal level variances present in typical SIGINT collection scenarios, a dynamic range of approximately 80dB is required. This is compatible with most SIGINT systems with a minimum detectable signal of -75 dBm and a maximum signal level of 0 dBm. Current state-of-the art in GaAs based ADC technology is limited to 60dB (12-bit) at 1 GHz. This performance is constrained by the *aperture jitter* of the current GaAs HBT technology (about 0.1 psec). The aperture jitter is the sample-to-sample variation in aperture delays, which can only be reduced by further decreasing the semiconductors 1/f noise.

On the basis of the LH- formula, from a system designer's perspective, the strategy to minimize overall phase noise consists in general of five basic steps. (a) One has to maximize the unloaded Q of the elements and the loaded Q of the circuit (Handel Q^{-4} law term), and (b) Maximize the reactive energy by using the highest possible RF voltage across the resonators. Since this is limited by the breakdown voltage, a wide gap device like a GaN FET should be used, if possible. (c) One has to select devices with a low corner frequency f_c and use a circuit design that minimizes quantum 1/f noise, and (d) Reduce phase perturbations by using high impedance devices such as GaN HFETs, where the signal-to-noise-ratio can be made very high. Furthermore, high biasing the active device (with feedback techniques) can minimize the modulation of the I/O dynamic capacitance. The capacitance modulation causes amplitude-to-phase conversion and hence introduces phase noise. Finally, one has to (e) select circuit topologies with lowest possible noise figures F, and (f) with the lowest possible quantum 1/f fluctuation of the dissipation γ present in the resonant system (oscillator). Another important factor is understanding the large-signal properties of the devices and circuits, e.g., the noise upconversion and the degree to which the overall system noise is determined by the low-frequency noise of the device. The high impedance and high breakdown voltage in GaN based devices offer unique new opportunities for the design of ultra-low phase noise amplifiers and systems. The design concepts will thus be drastically different from those used in the well-known GaAs counterparts.

B12. Quantum 1/f Proximity Effect in Nanotechnology

12.1 Introduction.

Electrical currents in nanostructures of any nature exhibit unusual 1/f noise. They are usually in the transition region between two radically different components of the fundamental quantum 1/f noise effect. This transition region between the coherent and conventional quantum 1/f effects is described by the relation

$$\alpha_H = (1/1+s)\alpha_{conv} + (s/1+s)\alpha_{coher} = (1/1+s)(4\alpha/3\pi)(\Delta v/c)^2 + (s/1+s)(2\alpha/\pi), \qquad (12.1)$$

for the quantum 1/f parameter α_H, where s is a parameter which governs the transition and depends on the concentration n of carriers and on the transversal cross section area Q of the quantum wire, conductor, semiconductor, sample or device, perpendicular to the direction of the current. Specifically,

$$s = 2nQr_0. \tag{12.2}$$

Here $r_0 = e^2/mc^2$ is the classical radius of the electron, $r_0 = 2.84\ 10^{-13}$cm. Therefore, s is twice the number of carriers in a salami slice of thickness equal with the classical diameter of the electron, normal to the direction of current flow. The resulting spectral density of fractional quantum 1/f current fluctuations $\delta j/j$ is then given by the quantum 1/f coefficient α_H through the relation

$$S_{\delta j/j}(f) = \alpha_H/fN. \tag{12.3}$$

This resulting total dependence on N shows that although the spectral density $S_{\delta j/j}(f)$ varies monotonously when the current-carrying cross section Q is reduced to nanoscale dimensions, there is a plateau on which the spectral density remains practically constant, while α_H changes its value. This plateau is visible in **Fig. 6** on page 44 below. Along that plateau, it is possible to reduce the cross section Q (and the number of carriers N) of the device without causing the 1/f noise to increase. However, according to Eq. (12.3), this implies that in the transition region the corresponding quantum 1/f coefficient α_H increases when the number of carriers per unit length of the device increases, as required by Eq. (12.1). Physically, this corresponds to the coherent magnetic interaction between the current carriers.

The question arises then: How far does one need to physically distance two longitudinal halves of the current-carrying sample, mentally separated along the center plane parallel to the current flow, in order to preclude the influence of the carriers from either half on the α_H of those in the other half?

This mutual enhancement of 1/f noise in the transition region between the predominantly coherent and the mainly conventional variation regions in cross section Q is what we will call "Induced 1/f Noise", or "Quantum 1/f Proximity Effect".

The effect is proportional to the mutual inductance M_{12} between the two parallel halves, or between two parallel currents at a distance d in general. This is shown in Sec. 12.2 below. The interaction between carriers, that is introduced by the magnetic field, causes the coherence present in the coherent quantum 1/f effect. There is a similarity between coherent quantum 1/f noise power and magnetic energy, or between conventional quantum 1/f noise and the kinetic energy of the drift motion. The total magnetic energy is not a sum of the contributions of individual carriers, but rather proportional to the square of such a coherent sum, i.e., to the squared magnetic field.

In conclusion, we expect the induced 1/f noise effect to vary with the distance d between two parallel elements of current proportionally to the mutual induction coefficient. This is applicable, e.g., to bundles of doped strands of DNA, used as conductors.

12.2 Derivation of the quantum 1/f proximity effect

Consider now two very long straight conductors of length L, of almost equal circular cross sections S_1 and $S_2 \approx S_1$, both with approximate radius of the cross section r, carrying currents $I_1 = nevS_1$ and $I_2 = nevS_2$ and separated by a distance *a* between their axes. Then the magnetic energy in Eq. (8.3) becomes, per unit length,

$$E_m = (1/L)\int(B^2/8\pi)d^3x \approx [(nevS_1/c)+(nevS_2/c)]^2\ln(R/r) - 2(nevS_1/c)(nevS_2/c)\ln(a/r). \qquad (12.4)$$

Substituting a/r=(R/r)(a/R) in Eq. (12.4), we obtain

$$E_m \approx [(nevS_1/c)^2+(nevS_2/c)^2]\ln(R/r) + 2(nevS_1/c)(nevS_2/c)\ln(R/a). \qquad (12.5)$$

Here R is a practically infinite large cutoff of the order of the radius of the circuit that contains the straight conductor of length L. Notice that for a=r, when the two conductors are in contact, the second term in Eq. (12.4) is zero and the magnetic energy is the well-known energy of a single cylindrical conductor of circular cross section S of radius r. On the other hand, for a=R the second term can be combined with the first term in Eq. (12.4) to yield simply the sum of the energies of the two infinitely separated parallel conductors. The approximation indicated in Eq. (12.4) uses the same effective radius r in the argument of the slowly varying logarithm present in the first term, as is used for each of the conductors separately. Note, however, that using 2r or $r\sqrt{2}$ would ignore the additional magnetic energy caused by currents present inside the 2r or $r\sqrt{2}$ radius, close to r, where the 2 conductors touch each other. That would severely under-estimate the magnetic energy.

The second term in Eq. (12.4) is the interaction energy of the two conductors, given by minus the work W_m done by us in the separation process against the electrodynamical attraction force between the conductors,

$$W_m = \int Fda = \int(2I_1I_2/ac^2)da, \qquad (12,6)$$

when the distance is increased from *r* to *a*. The integral from *r* to *a* in Eq. (12.5) yields the second term in Eq. (12.4) with opposite sign. The negative sign appears because in the separation process, the induced-Faraday-emf work W_b done by the system of energy $W=\Sigma I_i\Phi_i/2$ on the agency (e.g. a battery) to keep the currents constant is twice as large than W_m, and of opposite sign. In fact, while we are doing the separation work W_m on the system of two conductors, the system, in turn, must do on the battery twice the work W_m performed by us on itself, for the benefit of the agency that keeps the current constant in the two conductors. Indeed, denoting the fluxes through the circuits to which the two parallel conductors are belonging with Φ_1 and ϕ_2 respectively,

$$dW(I=const) = \Sigma I_i d\Phi_i/2; \qquad dW_b(I=const) = \Sigma I_i d\Phi_i; \qquad dW_m(I=const) = -\Sigma I_i d\Phi_i/2 \qquad (12.7)$$

with the sum Σ runs over i=1 and 2, we obtain for the differential dW of the energy W of the system of two conductors in the form

$$dW = dW_m + dW_b = -dW_m. \tag{12.8}$$

This explains the minus sign in Eq. (12.4).

Based on symmetry and $S_2 \approx S_1$, we use Eq. (12.5) to write the magnetic energy corresponding to the first conductor

$$E_{m1} \approx (nevS_1/c)^2 \ln(R/r) + (nevS_1/c)(nevS_2/c)\ln(R/a). \tag{12.9}$$

To generalize the definition of the parameter *s* of Eq. (8.5)-(8.6), we divide Eq. (12.9) by the kinetic energy of the drift component present in the motion of current carriers in the first conductor, per unit length

$$E_{k1} = \Sigma mv^2/2 = nS_1 mv^2/2. \tag{12.10}$$

This yields

$$s \equiv E_{m1}/E_{k1} \approx 2ne^2S_1/mc^2 \ln(R/r) + 2(ne^2S_2/mc^2)\ln(R/a), \tag{12.11}$$

or

$$s \approx s_1 + s_2\{[\ln(R/a)]/[\ln(R/r)]\}, \tag{12.12}$$

This form clearly displays the proximity effect in the second term of the expression obtained for the s-parameter in the presence of a similar current located at the distance a.

As we see from Eq. (12.1) and Fig. 6, due to the smallness of $\alpha_{conv}/\alpha_{coher}$ ($\approx 10^{-8}$ in our Example in Fig. 6) the 1/f noise spectral density given by Eq. (12.3) is practically proportional to s in the interval $10^{-5}<s<1$. This corresponds to the plateau in Fig. 6. What we have proven in Eq. (12.12) is that anywhere in this transition region of small to ultrasmall device sizes, the 1/f noise power doubles when we simply bring 2 wires or nanodevices closer to each other. When we separate them again, a 50% noise reduction can be achieved, by avoiding the proximity effect.

Our result can be easily generalized to arbitrary ratios between the parameters of the two wires, wells or devices, such as cross section, carrier concentration, drift velocities, etc. In this case the proximity effect will be given by a percentage larger than 100% in the smaller of the two wires or devices, and smaller in the larger one. The generalization to any number of conductors is also trivial. This effect, based on the quantum theory of 1/f noise, will negatively affect the efforts of nanoscale integration, if it is not avoided by quantum 1/f optimization of the layout.

In conclusion, we expect the induced 1/f noise caused by the proximity effect to vary with the distance *a* between two parallel elements of current as shown in Eq. (12.12). This result shows, e.g., for bundles of doped strands of DNA, used as conductors, that the 1/f noise will be reduced considerably in each strand, if the distance between them is increased.

B13. Low-Frequency Noise in Bent Ultrathin Semiconductors

In ultrathin semiconductor devices, surface scattering can no longer be ignored and significantly lowers the mobility of the carriers. This contributes a term in the scattering rate, which is proportional to λ/a in first approximation, where a is the thickness of the crystalline semiconductor sample. Since umklapp and intervalley scattering are the main limitation on the mobility of current carriers in silicon, and since they are affected by the largest conventional quantum 1/f effect, we expect a 1/f noise reduction in properly fabricated ultrathin semiconductor samples.

Ultrathin silicon samples and devices are obtained at the Univ. of California Irvine Microfabrication Laboratory in the Engineering Gateway building. One of the methods used by us involves uniform etching to reduce the thickness of the sample by an order of magnitude.

To estimate the conventional quantum 1/f effect (CQ1/fE) in ultrathin Si devices and integrated circuits (IC), we need to also include the effect of the reduction in carrier lifetime τ due to the surface recombination rate. This increases the 1/f noise in junction devices, because the quantum 1/f effect is inversely proportional to the number N of carriers which have participated in the generation-recombination-limited current transport through the various p-n junctions. This number is, however, given by the GR component of the current I multiplied by the lifetime τ of the carriers.

Assuming small samples, the CQ1/fE is applicable and is affecting surface scattering rates according to the fundamental formula

$$S_{\delta\Gamma/\Gamma} = (4\alpha/3\pi)\langle(\Delta v/c)^2\rangle. \tag{13.1}$$

The brackets indicate a statistical average over the parameters of a surface scattering. We obtain the 1/f noise power spectrum by substituting a considerably increased thermal velocity for $\Delta\mathbf{v}$, because of the surface potential ($V_o>0$ in n-type) in the presence of an accumulation layer, which is not applicable for $V_o<0$ (depletion in n-type material). However, the case of inversion would lead again to a 1/f noise increase in spite of $V_o<0$, but there is also a carrier identity switch which affects the result in this case, due to the difference in effective mass and scattering mechanism.

13.1 Surface scattering and bulk scattering

The total scattering rate is the sum of surface and bulk scattering rates. Therefore, the mobility μ will be determined from the mobility μ_b existent in the absence of surface scattering in the bulk material and from the mobility μ_s which would be present in that sample in the absence of bulk scattering

$$1/\mu = 1/\mu_b + 1/\mu_s. \tag{13.2}$$

The quantum 1/f fluctuations will therefore satisfy the relation

$$\delta\mu/\mu^2 = \delta\mu_b/\mu_b^2 + \delta\mu_s/\mu_s^2. \tag{13.3}$$

Consequently, the CQ1/fE spectral density $S_{\delta\mu/\mu}(f) \equiv \langle(\delta\mu/\mu)^2\rangle_f$ satisfies the relation

$$S_{\delta\mu/\mu} = (\mu^2/\mu_b^2)\langle(\delta\mu_b/\mu_b)^2\rangle_f + (\mu^2/\mu_s^2)\langle(\delta\mu_s/\mu_s)^2\rangle_f. \tag{13.4}$$

For the quantum 1/f noise in the bulk mobility we write

$$\langle(\delta\mu_b/\mu_b)^2\rangle_f = (4\alpha/3\pi Nf)\langle(\hbar\,\Delta k/mc)^2\rangle = (4\alpha/3\pi Nf)(0.75h/amc)^2, \tag{13.5}$$

where m is the effective mass of the carriers, and the effective Δk was taken to be 0.75 G. Here G is the smallest reciprocal lattice vector $2\pi/a$, where a is the lattice constant and $h=2\pi\hbar$. Finally, $\alpha=e^2/\hbar c$ is Sommerfeld's fine structure constant and N is the number of carriers in the sample.

The conventional Q1/fE in the surface-scattering-limited mobility μ_s is obtained from Eq. (13.1) by substituting

$$(\Delta v/c)^2 = 6kT/mc^2 + 2eV_o/m. \tag{13.6}$$

This yields

$$\langle(\delta\mu_s/\mu_s)^2\rangle_f = (4\alpha/3\pi Nf)[6kT/mc^2 + 2eV_o/mc^2], \tag{13.7}$$

where e is to be replaced by -e, and m by m' the case of inversion, m and m' being the effective masses of the carriers.

The final expression for the resulting power spectrum of quantum 1/f mobility fluctuation is thus

$$S_{\delta\mu/\mu} \equiv \alpha_{conv}/Nf = (4\alpha/3\pi Nfc^2)[(\mu/\mu_b)^2(0.75h/am)^2 + (\mu/\mu_s)^2(6kT/m + 2eV_o/m)]. \tag{13.8}$$

In this expression the quantity in round brackets in the second term on the right hand side is always smaller than the corresponding round bracket present in the first term, corresponding to lattice scattering, and characteristic for the bulk material. However, the relative contribution of the two terms on the right hand side depends on the sample thickness. For a given sample this second term can be further reduced by treating the surface in order to obtain a depletion layer (with a small $V_o<0$ for n-type material).

13.2 Influence of dislocations arising from bending deformation

Uniform bending with a radius of curvature R will generate a surface density of dislocations of $\rho=1/aR$ and an additional volume density of defects $n_{dis}=1/a^2R$ in the given ultrathin sample. Assuming we know the measured mobility μ_o of the given sample before bending, the theoretical mobility $\mu_l=\mu_{lattice}$ of the ideal sample with no defects (limited by phonon

scattering, intervalley and umklapp only) and the concentration of defects n_{odef} in the given sample before bending, we can derive for the quantum 1/f noise spectral density of fractional fluctuations expected in the bent ultrathin sample the approximate formula

$$S\delta\mu/\mu = \{(\mu_o^2)/[(1+r)\mu_l - r\mu_o]^2\}S^{latt}_{\delta\mu/\mu}(f), \tag{13.9}$$

in which $r=n_{dis}/n_{odef}$, and $S^{latt}_{\delta\mu/\mu}(f)$ is the theoretical quantum 1/f spectral density affecting μ_l in an ideal sample with no defects, being caused by phonon scattering, intervalley and umklapp only. This formula is obtained by neglecting the quantum 1/f noise of defect scattering (both ionized or neutral, both impurity defects and lattice defects) compared to the much larger quantum 1/f noise of lattice scattering, including phonon scattering, intervalley and umklapp in the ideal lattice.

If a lattice constant of a=1Å and a bending radius of curvature R=10 cm are considered, the resulting dislocation densities of $\rho=10^7$ cm^{-2} and $n_{dis}=10^{15}$ cm^{-3} have to be compared with the pre-existing concentration of defects n_{odef}. Assuming $n_{odef}=10^{16}$ cm^{-3}, we obtain r=0.1. The resulting correction is a small reduction in the expected noise. However, this calculation neglects all current-redistribution effects which result from a non-uniform distribution of dislocations introduced by bending. It also neglects the effect of the decreased lifetime of the carriers in bent ultrathin ICs, in particular on the junction devices or on other unwanted junctions present in the IC. All these effects result in increased conventional quantum 1/f noise. The increased non-uniformity of the current distribution also results in an increase of the coherent quantum 1/f effect present in the larger samples as we see in the next section.

13.3 Deviations from the general 1/N dependence of the 1/f noise in the presence of a coherent quantum 1/f vestige

At this point we ask how the Q1/fE changes when we scale a macroscopic conductor, semiconductor, sample or device down to ultrasmall thickness. The transition from coherent to conventional Q1/fE is given by the relation

$$\alpha_H = (1/1+s)\alpha_{conv} + (s/1+s)\alpha_{coher} = (1/1+s)(4\alpha/3\pi)(\Delta v/c)^2 + (s/1+s)(2\alpha/\pi), \tag{13.10}$$

where s is a parameter which governs the transition and depends on the concentration n of carriers and on the transversal cross section area Q of the conductor, semiconductor, sample or device, perpendicular to the direction of the current. Specifically,

$$s = 2nQr_0. \tag{13.11}$$

Here $r_0 = e^2/mc^2$ is the classical radius of the electron, $r_0= 2.84\ 10^{-13}$cm. Therefore, s is twice the number of carriers in a salami slice of thickness equal with the classical diameter of the electron, normal to the direction of current flow (see Fig. 5). The resulting spectral density of fractional quantum 1/f fluctuations is then given by the quantum 1/f coefficient α_H through the Hooge relation

$$S_{\delta j/j}(f)= \alpha_H/fN. \tag{13.12}$$

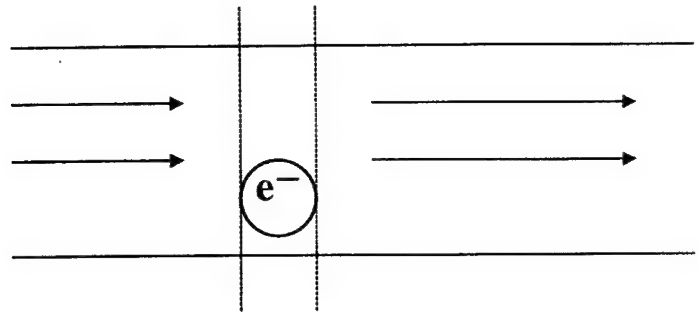

Fig. 5: To define the parameter s, a slice as thick as the classical electron radius is considered. The number of carriers in it is s.

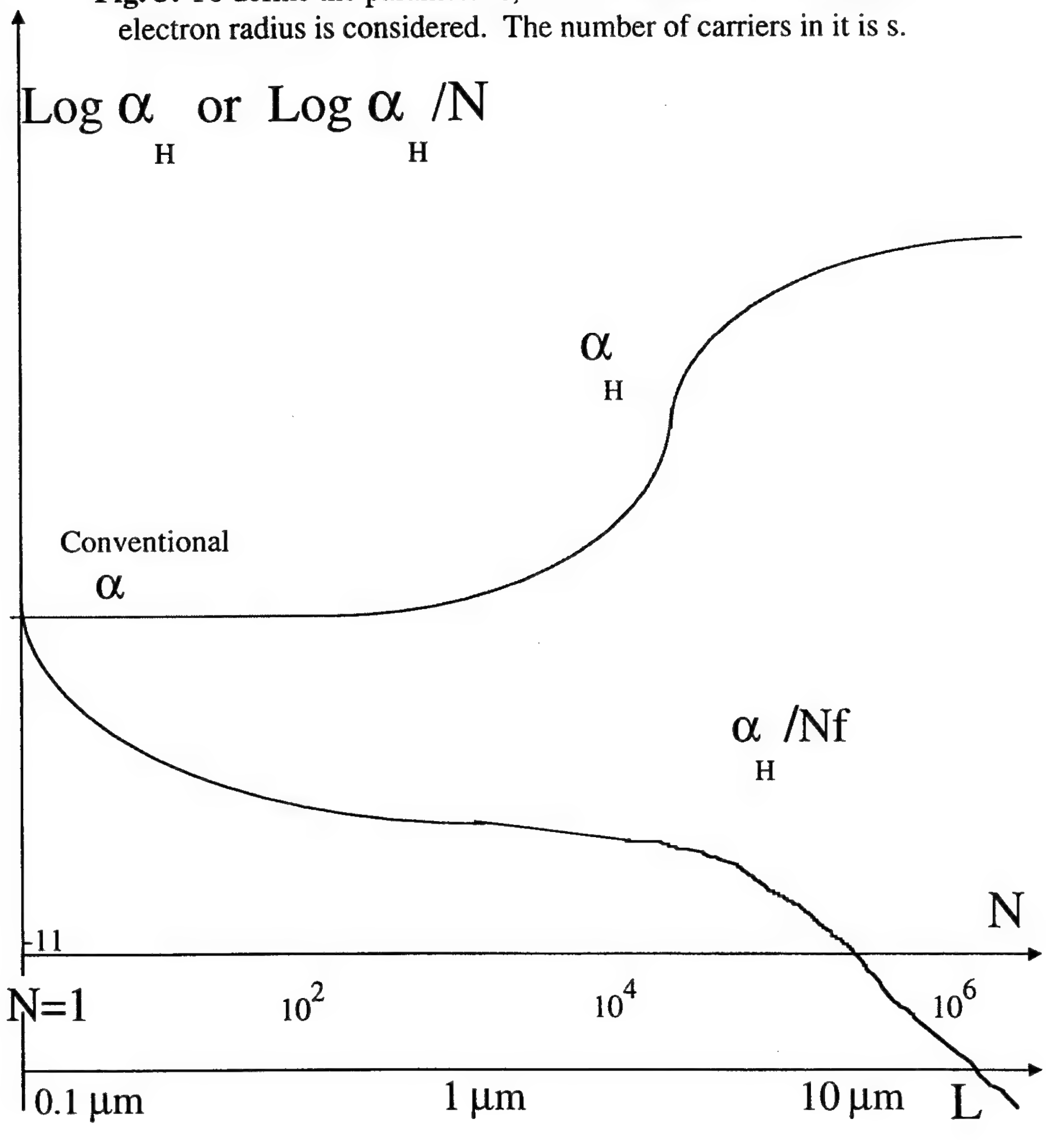

Fig. 6: The quantum 1/f parameter α_H and the resulting spectral density $S_j=\alpha_H/Nf$ as a function of the number of carriers in the sample N or of the cross section size L

This resulting total dependence on N is shown qualitatively in Fig. 6 above for the transition from macroscopic dimensions to ultrasmall samples. It shows that although the spectral density varies monotonously when the thickness of the sample and thereby also the size of the current-carrying cross section is lowered down to nanoscale dimensions, there is a plateau on which the spectral density remains constant, while α_H changes its value.

14. Quantum 1/f Effect in Spin-Polarized Transport and Spintronic Devices

The spin-polarized leakage current passing through a closed spin-valve is caused by electron spin-flip processes. The rate of these processes controls the rate of current flow. Without a spin-flip, the electron can't go through the valve. The electronic spin-flip rate is affected by quantum 1/f noise because the spin-flip emits bremsstrahlung just like any sudden current change $\Delta\mathbf{J}=(e/L)\Delta\mathbf{v}$ would do. The conventional quantum 1/f effect (Q1/fE) in any rate Γ or cross section σ is a macroscopic quantum phenomenon described by the quantum 1/f engineering formula,

$$S_{\delta\Gamma/\Gamma}(f) = S_{\delta\sigma/\sigma}(f) = S_{\delta j/j}(f) = (4\alpha/3\pi f N)(\Delta\mathbf{v}/c)^2. \tag{14.1}$$

Here $S_{\delta\Gamma/\Gamma}(f)$ is the spectral density of fractional fluctuations in current, $\delta j/j$, in scattering or recombination cross section $\delta\sigma/\sigma$, or in any other process rate $\delta\Gamma/\Gamma$. $\alpha=e^2/\hbar c = 1/137$ is Sommerfeld's fine structure constant, a magic number of our world depending only on Planck's constant $\hbar$, the charge of the electron e and the speed of light in vacuum c. $A=2(\Delta v/c)^2/3\pi$ is essentially the square of the vector velocity change $\Delta\mathbf{v}$ of the scattered particles in the scattering process whose fluctuations we are considering, in units of c. Finally, N=LN' is the number of particles used to define the notion of current j, of cross section σ or of process rate Γ.

This applies to the *quantum 1/f fluctuations of the electronic spin-flip rate,* or *decoherence rate*, as mentioned above. Decoherence is caused by the elementary spin-flip of a nucleus due to its various interactions. The particular nature of these is not important here, due to the well-known quantum 1/f universality that characterizes all infrared divergence phenomena. The rate of this process has quantum fluctuations according to Eq. (14.1). It reduces the total magnetic moment M of the sample by the magnetic moment $\mu = e\hbar/2mc = 1$ Bohr magneton of a single electron spin undergoing a change of one $\hbar$ in its spin projection. The current change $e\Delta\mathbf{v}$ causing bremsstrahlung is here $(\Delta\dot{\mathbf{M}})/e$, the change in the rate of demagnetization caused by the emission of an energy quantum, a photon. This yields

$$S_{\delta\Gamma/\Gamma}(f) = 4\alpha\langle(\Delta\mathbf{v})^2\rangle/3\pi f c^2 = 4\alpha\langle(\Delta\dot{\mathbf{M}})^2\rangle/3\pi f e^2 c^2. \tag{14.2}$$

Let N be the number of elementary magnetic dipoles $\mu=e\hbar/2mc$ present in the magnetic induction field B and aligned parallel to it. Applying a variation $\Delta N=2$ for a spin reversal, we get

$$\Delta n/n = \Delta N/N = |\Delta\dot{\mathbf{M}}|/|\dot{\mathbf{M}}|, \text{ or } \langle(\Delta\dot{\mathbf{M}})^2\rangle = \langle(\dot{\mathbf{M}})^2\rangle/N^2 = 8\mu^4H^2N^2/\hbar^2, \tag{14.3}$$

where we used Larmor's theorem $\dot{\mathbf{M}} = \boldsymbol{\omega}\times\mathbf{M}$, with $\boldsymbol{\omega}=N\mu\mathbf{H}/\hbar$. Substituting $\Delta\dot{\mathbf{M}}$ into Eq. (14.2), we get

$$S_{\delta j/j} = \Gamma^{-2}S_\Gamma(f) = 32\alpha\mu^4H^2N^2/3\pi f e^2c^2\hbar^2. \tag{14.4}$$

This is the spectral density of fractional quantum 1/f fluctuations in the rate Γ of spin-flip or decoherence (electrodynamical Q1/fE only). This spectral density of fractional fluctuations will affect the spin-polarized leakage current j through the device. There is also shot noise $S_{\delta j/j}$=2ej.

C. CONCLUSIONS AND RELEVANCE FOR U.S. AIR FORCE, DOD AND CIVILIAN APPLICATIONS

The research performed as part of this Grant project, under the direction of Dr. Gerald L. Witt, AFOSR/NE, has considerable relevance for the objectives of the U.S. Air Force, for DOD in general, and for many civilian industrial applications.

Indeed, the space and aerospace battle environment may involve nuclear exchanges, and this requires **radiation hardening** (Sec. B1-B4) of the airplanes and of their electronic and communications equipment. In addition there is a threat to the electronic equipment arising from some of the directed energy weapons. Even in the absence of conflict, the cosmic and solar radiation represents a threat, particularly in the region of the van Allen radiation belts, or the radiation zone of other planets. One of the major components of the radiation threat to electronic components is the instantaneous release of large concentrations of current carriers in semiconductors from sudden irradiation (for that we make only general suggestions, Sec. B3)). Another is the creation of a large concentration of defects in the lattice of the semiconductor materials used in devices, and the resulting change in the device parameters and in its electronic noise Sec. (B1-B2). Low frequency noise, in particular 1/f noise is particularly damaging, because it appears also as ***phase noise*** (Sec. B11), destabilizing RF and microwave oscillators and systems. The quantum 1/f theory provides a scientific understanding and an exact analytical description of 1/f noise and phase noise at every level, in materials, devices and systems. This description is in terms of concrete engineering design and optimization formulas, replacing the earlier empirical approach. This provides a clear superiority of equipment developed on scientific basis.

The formulas and concepts developed in this research show for the first time, from first principles, how the **1/f noise depends on the radiation dose and on its type**, in different types of electronic devices (Secs. B1-B2). This influences the selection of the devices used to design certain electronic systems with radiation hardening in mind, such as amplifiers, oscillators, and systems based on them, such as radars and communication systems, sensors, guidance and control units, etc.

An essential component of military and civilian electronic communications is **the antenna**. It is shown here to have **1/f noise** hidden **in** its so-called **radiation resistance** (Sec. B6). Multiple satellites and arrays, used to bundle a beam very well, are both affected by it, and we show here which way. Again, we develop the concepts and the corresponding engineering formulas for the first time.

The importance of **phase noise** for the Air Force is tremendous. A 10 dB reduction in the noise floor will reduce the bit-error-rate by a factor of 10^{-6} in DSP systems that process real-time inputs in a battlefield environment. In a Doppler radar, from the R^{-4} law, a 24 dB reduction in the noise floor corresponds to a 4 fold increase in range R. The new generation of low-noise electronic devices important for the Air Force, revolutionizing both high power systems (radars, radio, TV, microwave and THz transmitters, etc.) and ultra-low power (mini-receivers, MEMS sensors, MEMS frequency standards, THz receivers, etc.) is becoming possible due to advances in material processing and due to our better handle on 1/f noise and the resulting **phase noise**

(Sec. B5). This poorly understood subject was described with the help of the so-called ***Leeson*** formula. The present project has resulted in a modification of this basic engineering formula with an additional term that is dominant for high tech, high-stability oscillators in any frequency domain. This fundamental breakthrough is of tremendous practical importance for the modern high-tech industry. It will be reflected in the quality of future military and civilian gadgets across the board. It is well worth the sacrifice that the present author has brought for a long time, and particularly during this project, under most difficult conditions, and with little support, cooperation, understanding and recognition. To be able to carry out all projects and realize the discoveries that solved various puzzles and paradoxes, the author often had to postpone publication of major results in the open literature, and to use primarily invited or contributed papers at conference proceedings as his communication with peers. All this would not have been possible without the concrete, unwavering, scientific, moral and material support received by the author from AFOSR through Dr. Gerald Witt.

The quantum 1/f formula was used during this Grant to provide for the first time a scientific calculation and a practical engineering formula for **1/f noise in GaN/AlGaN HFETs** (Sec. B7). The agreement with the experimental data of professors Balandin, Wang, Vishvanatan et al. from the University of California is very good. These HFETs are of tremendous importance for the Air Force and DOD in general, being essential for the new generation of solid-state high-power RF and microwave generators.

Resonant tunneling diodes have a negative differential resistance region in their current voltage characteristic. **RTDs** (Sec. B8) are ideal for microwave generation up to the THz region. The quantum 1/f theory was applied by the author during this grant to find both the 1/f noise of the RTD, and the resulting phase noise of the oscillator (generator with resonator) based on such an RTD. This allows for the first time for a scientific optimization of materials, devices and systems for these application. They are also of considerable importance for the mission of the Air Force.

Of major importance for DOD and for the Nation in general, in particular after the September 11, 2001 tragedy, is the early detection of an attack with biological or chemical weapons, in particular a terrorist attack with anthrax, smallpox, the plague, poliomyelitis, nerve gas, etc. In June 2001, at the Seattle Frequency Control Symposium the author gave an invited talk on his research on the quantum 1/f limits of quartz microbalance (BAW), and SAW, sensors that are activated with the antigens displaying affinity to one of the pathogenic agents mentioned above. This research, giving for the first time the quantum limits of, and optimization tools for, the **biological and chemical sensors**, (Sec. B9) was done under this Grant. In general, the quantum 1/f theory and engineering formulas developed here allow for the optimization of both design and implementation of novel, completely monolithic integrated MEMS resonators and sensors.

The FET-based sensors and other sensors included in the "electronic nose" have also been perfected now to the point where they have reached their quantum limit. They are therefore limited by the quantum 1/f effect, and subject to Q1/f optimization. There also was successful work on Quantum 1/f Effect in Spin-polarized Transport (Sec. B14) during this Grant.

Another problem of practical importance is the effect of mechanical bending on ultra-thin semiconductor samples and credit card shaped **ultra-thin integrated circuits**. The deformation causes an array of dislocations, and a change in 1/f noise that has been calculated with the quantum 1/f theory (Sec. B13).

Finally, we have continued our investigation of the fascinating transition region between coherent and conventional quantum 1/f effect, because it corresponds to the size of present sub-

micron and nano-devices. This led to the introduction of the "**quantum 1/f proximity effect**" (Sec. B12) for the first time during the present grant. This fundamental effect causes the 1/f noise in a semiconductor wire to depend on the presence of other similar wires in the vicinity, carrying part of the current. It is like a mutually induced 1/f noise, present only in this transition region of sizes. This is startling to anyone familiar with the traditional phenomenology of 1/f noise, but unaware of the details of the quantum 1/f theory.

D. PAPERS WRITTEN/PUBLICATIONS

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D1. Examples of Quantum 1/f Papers recently published by others

(See "Quantum 1/f Noise" Index on MELVYL, the University of California Science Data Base and Library System for more recent titles)

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b) Worked as co-editor of the new edition of K.W. Böer's "Survey of Semiconductor Physics", by J. Wiley Publ. Co.

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